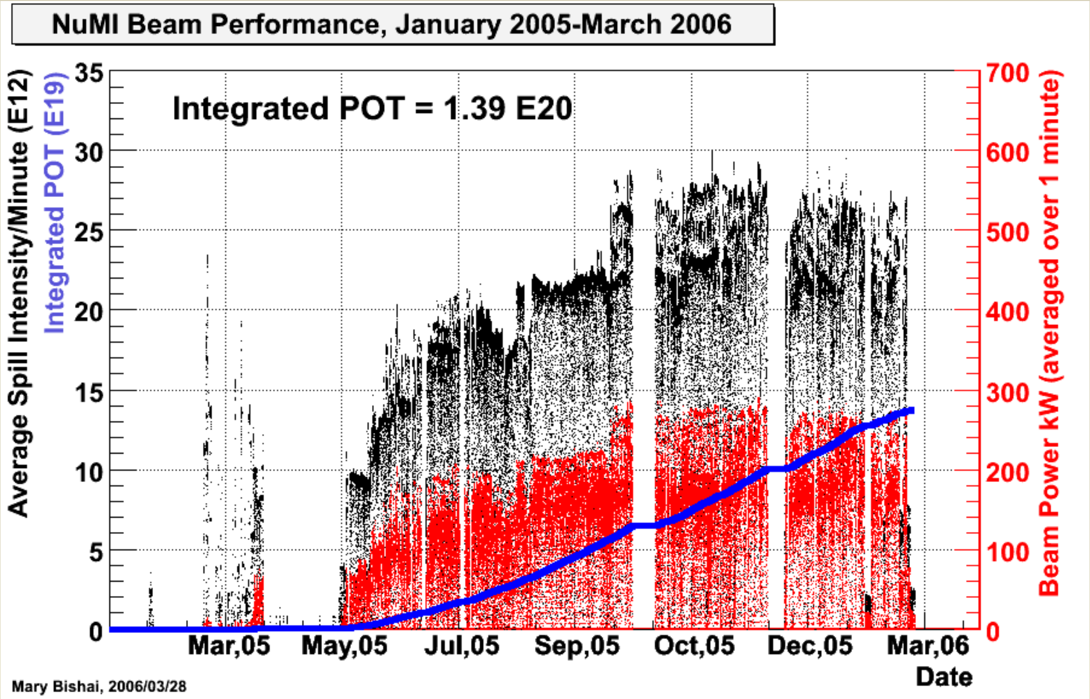
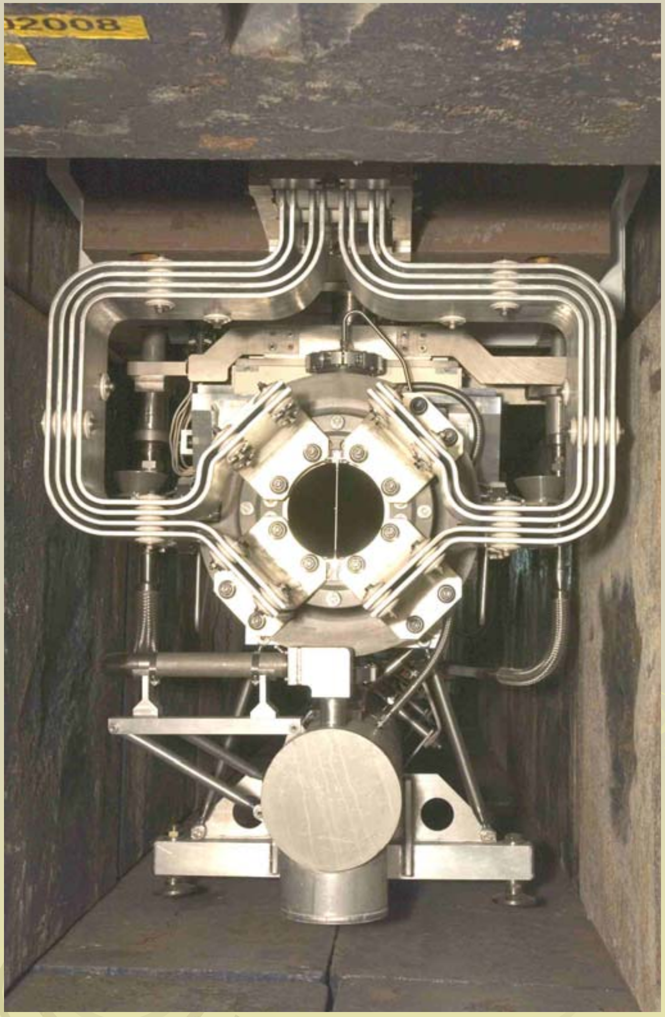
The NuMI Beam :

A First Year of Operation

Sam Childress, Fermilab





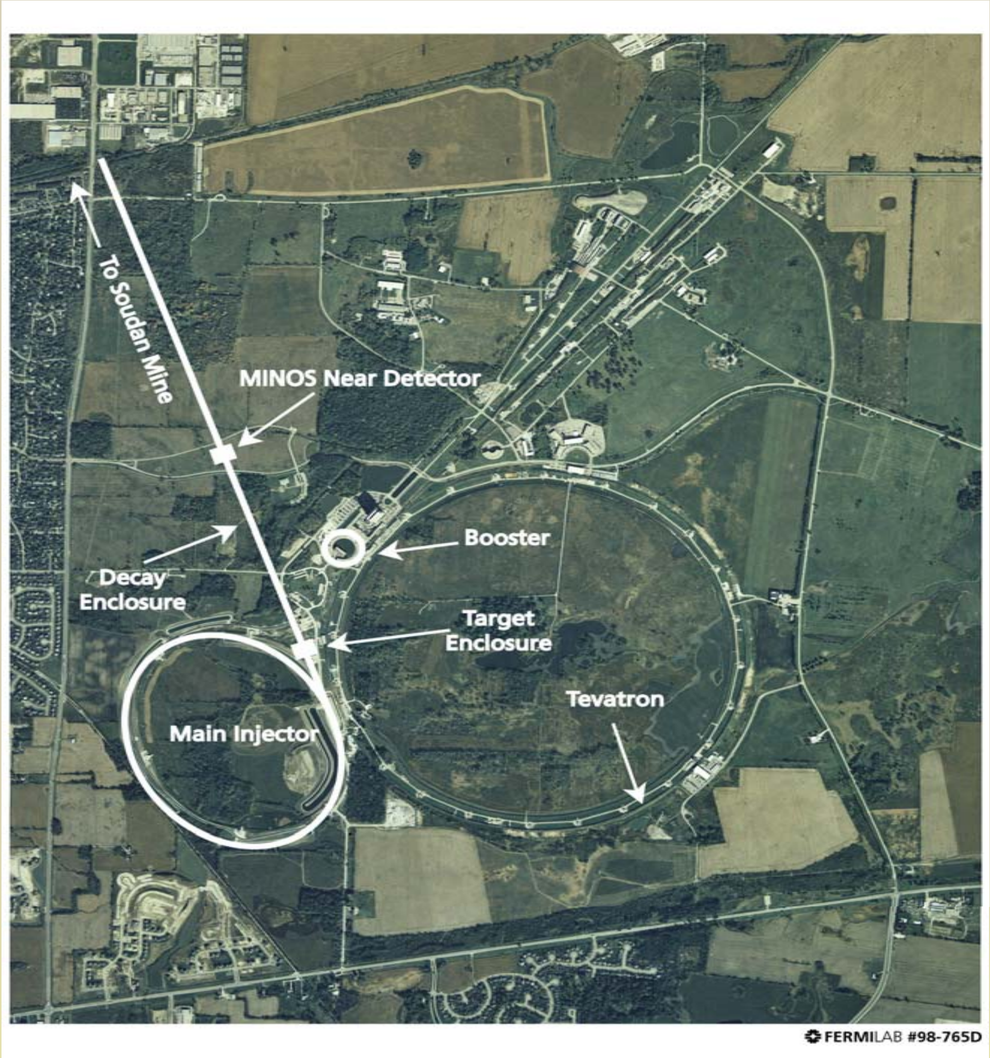
Successes & Challenges

Presentation Outline

- NuMI / MINOS Overview
- Beam System Components
- Beam Commissioning & Transition to Operations
- NuMI Beam Performance: Successes and Challenges
- Summary

A previous AB seminar at an earlier stage of NuMI beam operation was given 29 Sept. 2005

NuMI: Neutrinos **at the Main Injector**



Fermilab to
Soudan, Minnesota

NuMI: ν's at the Main Injector (Focus of this talk)
MINOS: Main Injector Neutrino Oscillation Search

A neutrino beam from Fermilab to northern Minnesota

- 120 GeV **protons** from the Main Injector (400 kWatts)
- Production of a high power **neutrino** beam
- On-axis over **735 km** to Soudan mine (MINOS experiment)

A large near hall at ~ 1 km from the target

- MINOS near detector (980 Tons)

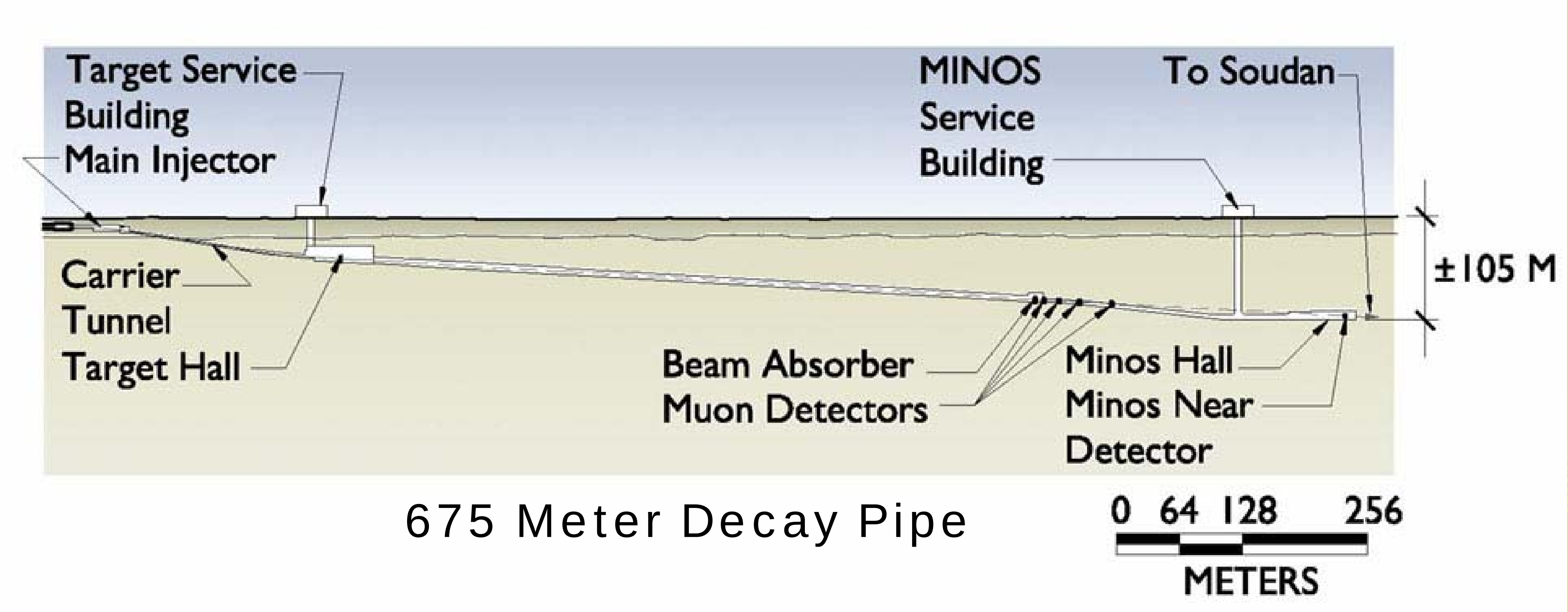
A deep underground hall at Soudan, Minnesota

- MINOS far detector (5400 Tons)

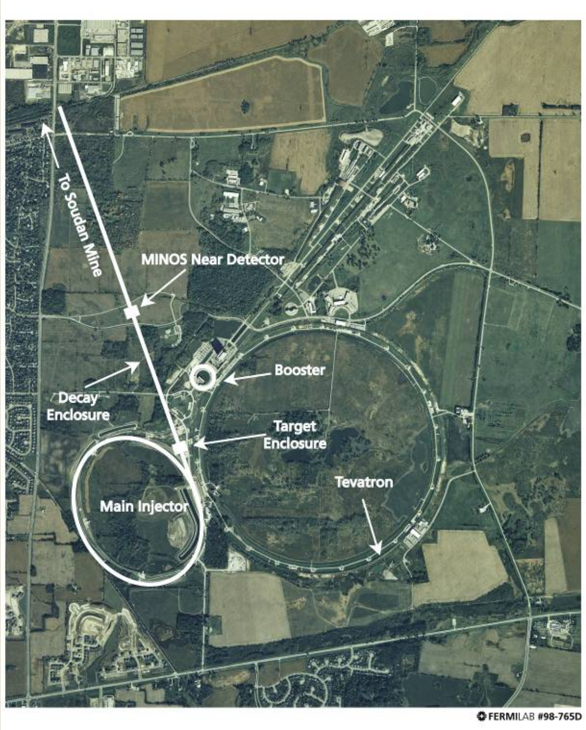
Key NuMI Project Dates

- Initiated in late 1998
- Facility construction completed in Fall 2003
- Technical component installation from 2003 to early 2005
  - Extraction & primary beam components in Main Injector interlock area installed during scheduled machine shutdown times in 2003 & 2004.
- Beam commissioning starts Dec. 2004
- Completion of project goals Jan. 2005
  - DOE Approval for Operation

Elevation View of the NuMI/MINOS Project on Fermilab Site



Key NuMI Beam System Features



Main Injector & NuMI

Main Injector is a rapid cycling accelerator at 120 GeV

- from 8 to 120 GeV/c in ~ 1.5 s

up to 6 proton batches (~ 5×10^{12} p/batch) are successively injected from Booster into Main Injector

Main Injector in parallel provides protons for the Collider program (anti-proton stacking)and transfers to the Tevatron) and NuMI

total beam intensity ~ 3×10^{13} ppp, cycle length 2 s

Mixed mode: NuMI & Pbar stacking

- two single turn extractions within ~ 1 ms:
  - 1 batch to the anti-proton target, 5 batches to NuMI
- Normally the batch extracted to the Pbar target comes from **the merging of two Booster batches ("slip-stacking") (up to 0.8×10^{13} ppp)**
- ***the default mode of operation is mixed-mode with slip-stacking***

NuMI only

- up to 6 Booster batches extracted to NuMI in ~ 10 μs

Extraction from Main Injector

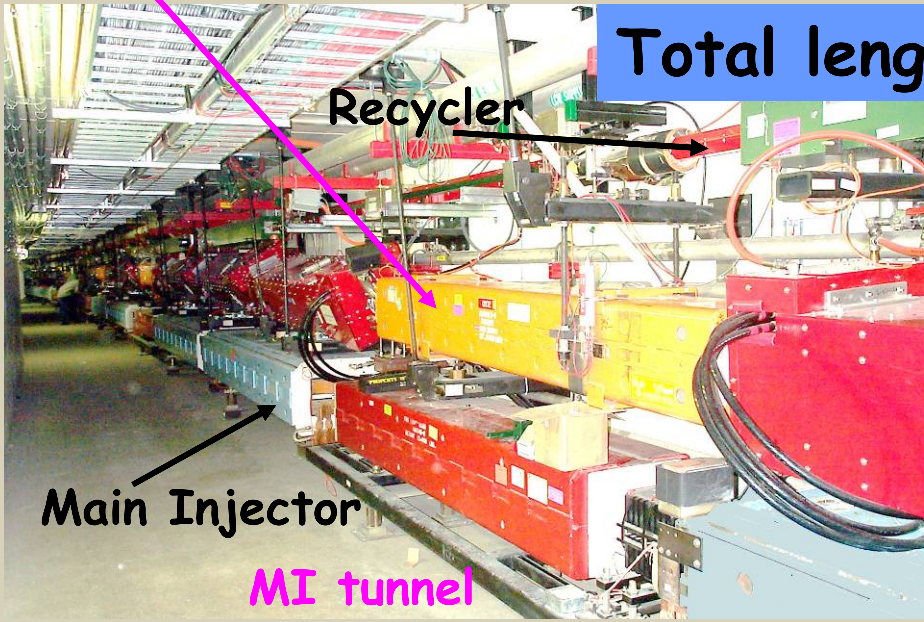
Kickers & Septa

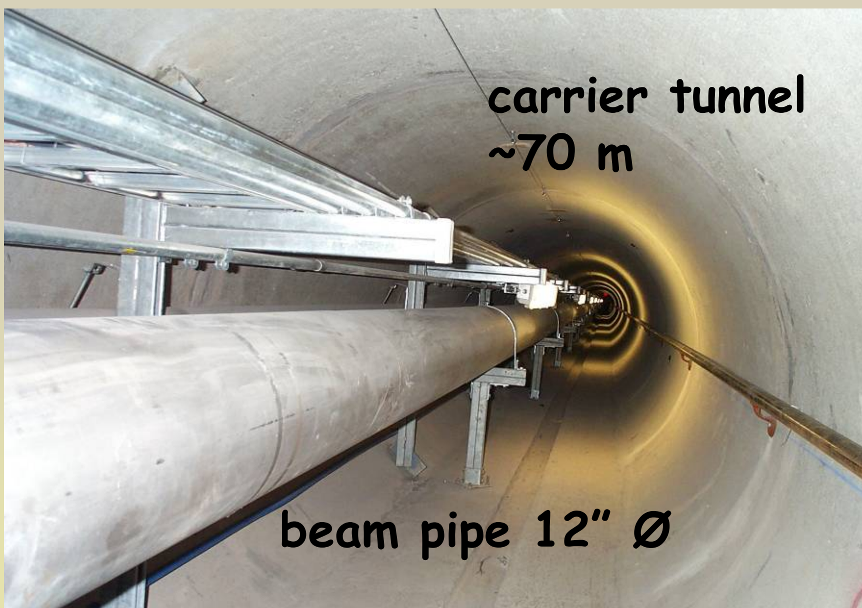
Primary Proton Line

NuMI line

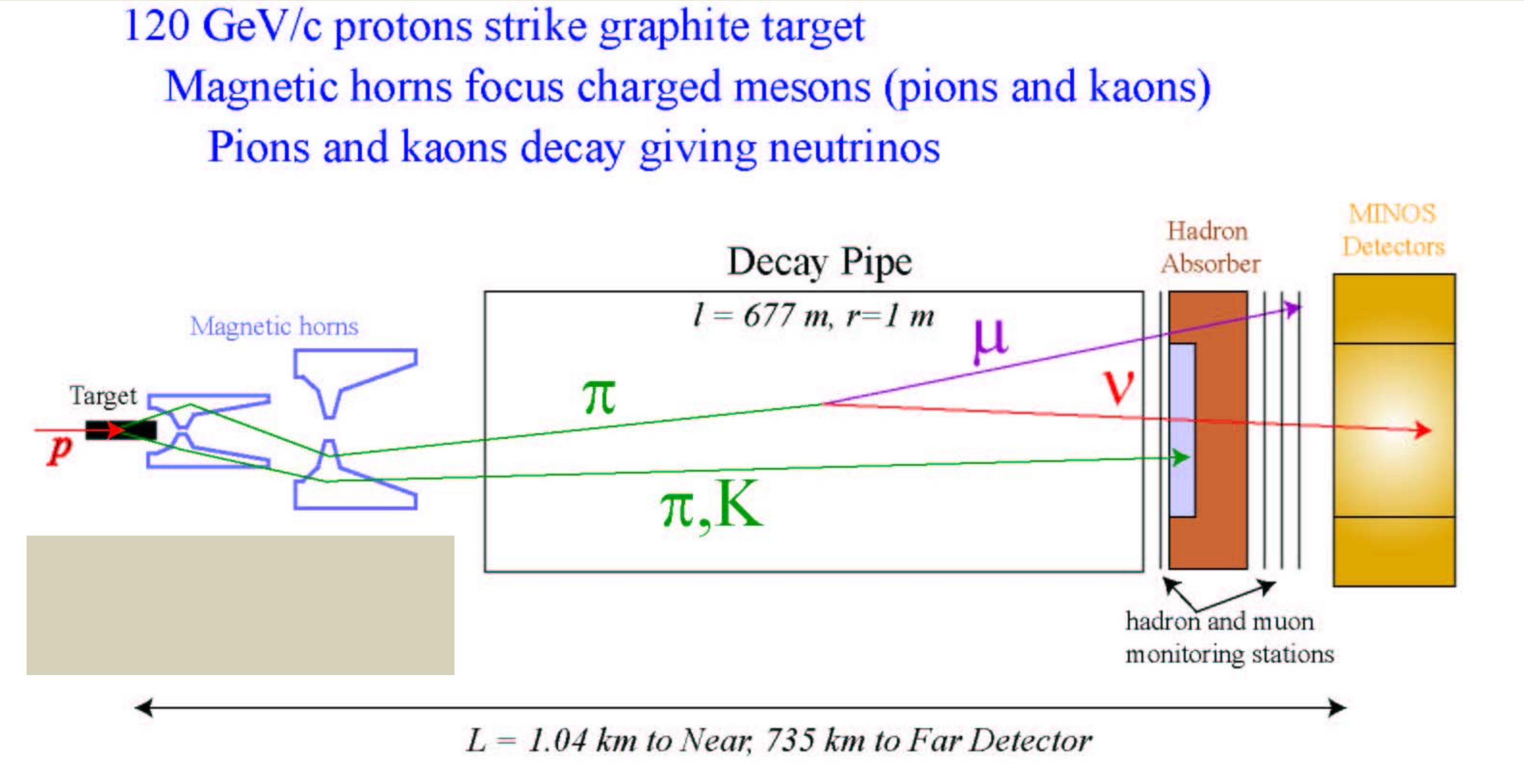
bending down by 156 mrad

Total length ~ 350 m

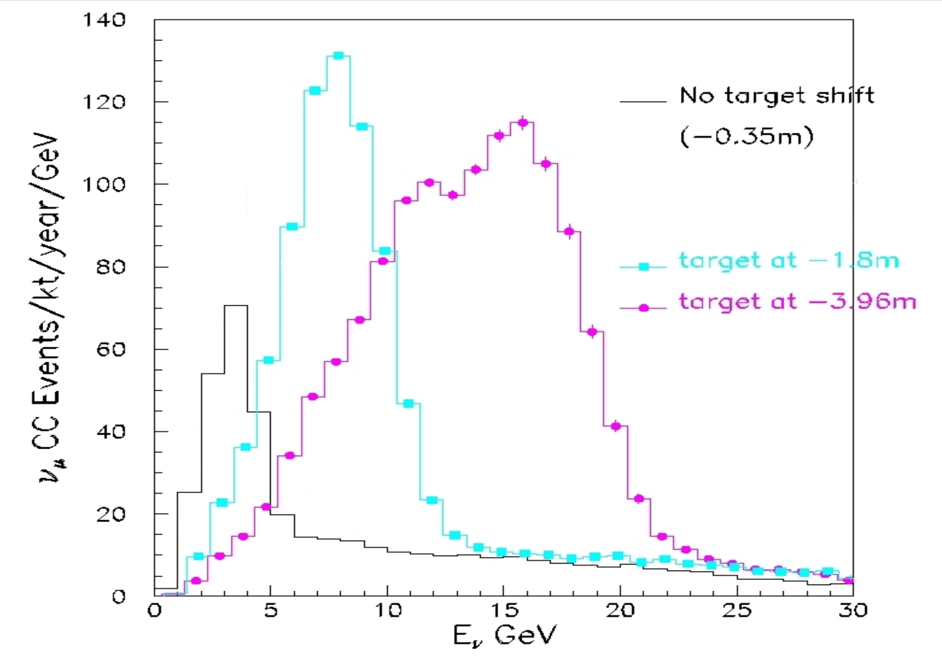


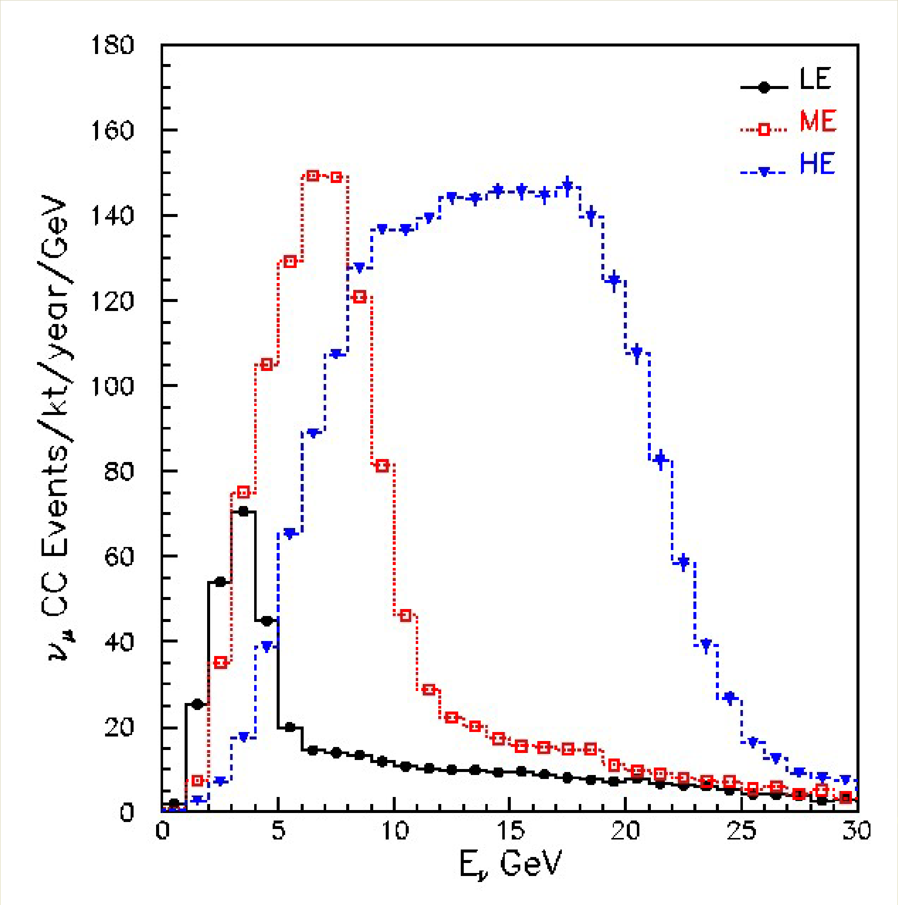


ν Production for NuMI



Reasonable Variable Energy ν Beam by Moving Target distance from Horn 1





"Semi-beams"

*Just moving LE target - **remotely***

Full Beams

Move Horn 2

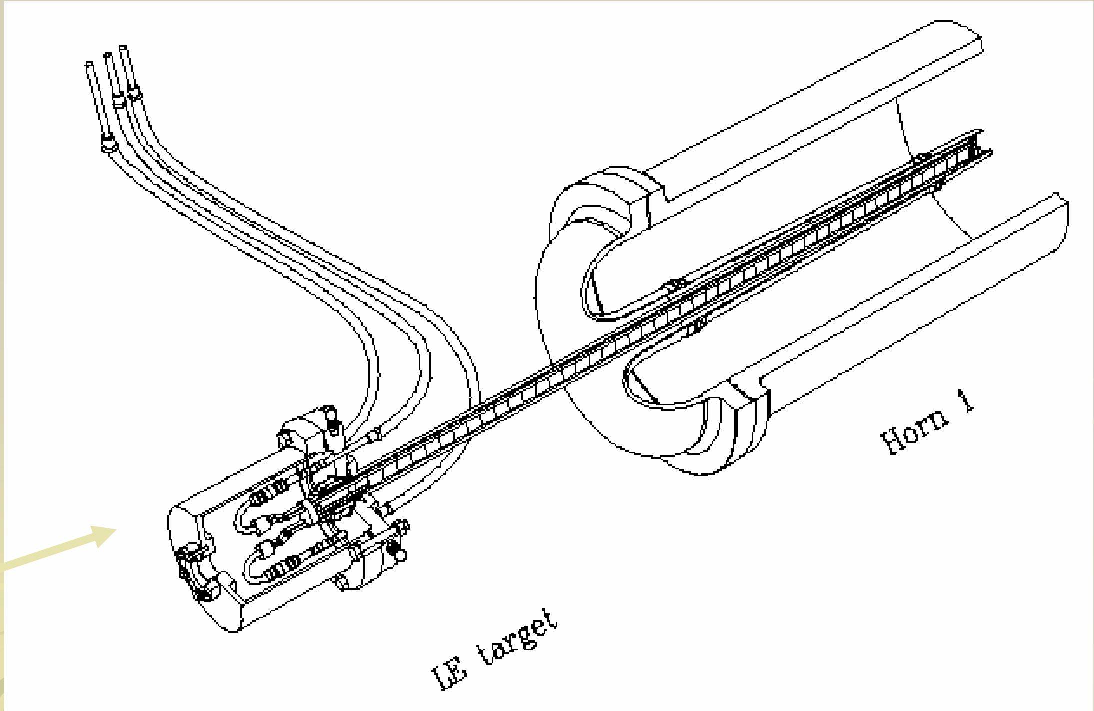
Graphite Target

Graphite Fin Core

2 interaction lengths

Water cooling tube

provides mechanical support

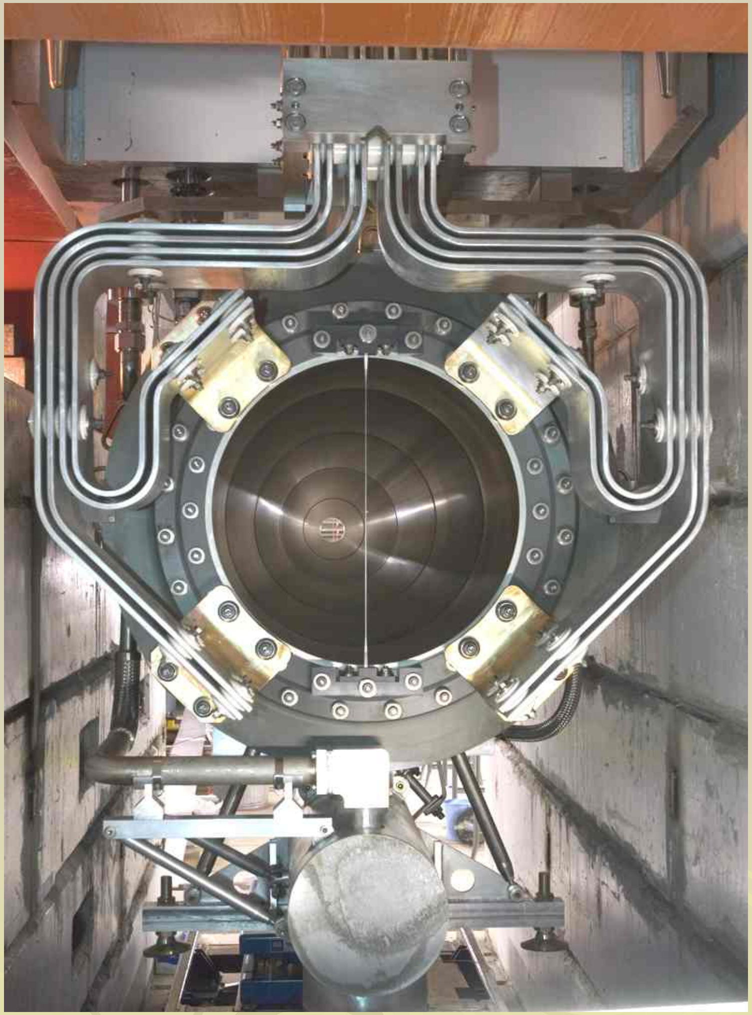


Low Energy Target fits in horn

without touching

Horn System – 2 horns

(shown in work cell, hanging from support module)



Work Cell
Mount/Dismount Components

Connections are all done through the module by person on top of work cell

Railing

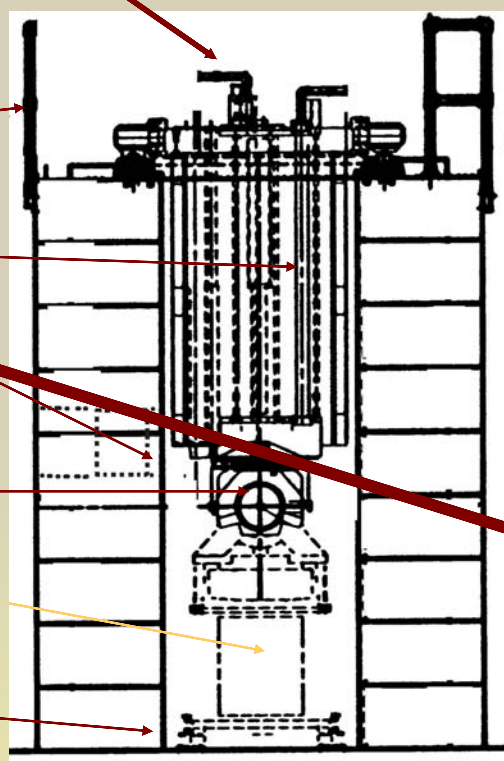
Module

Lead-glass window

Horn

Remote lifting table

Concrete walls



3 m

Hadron Absorber

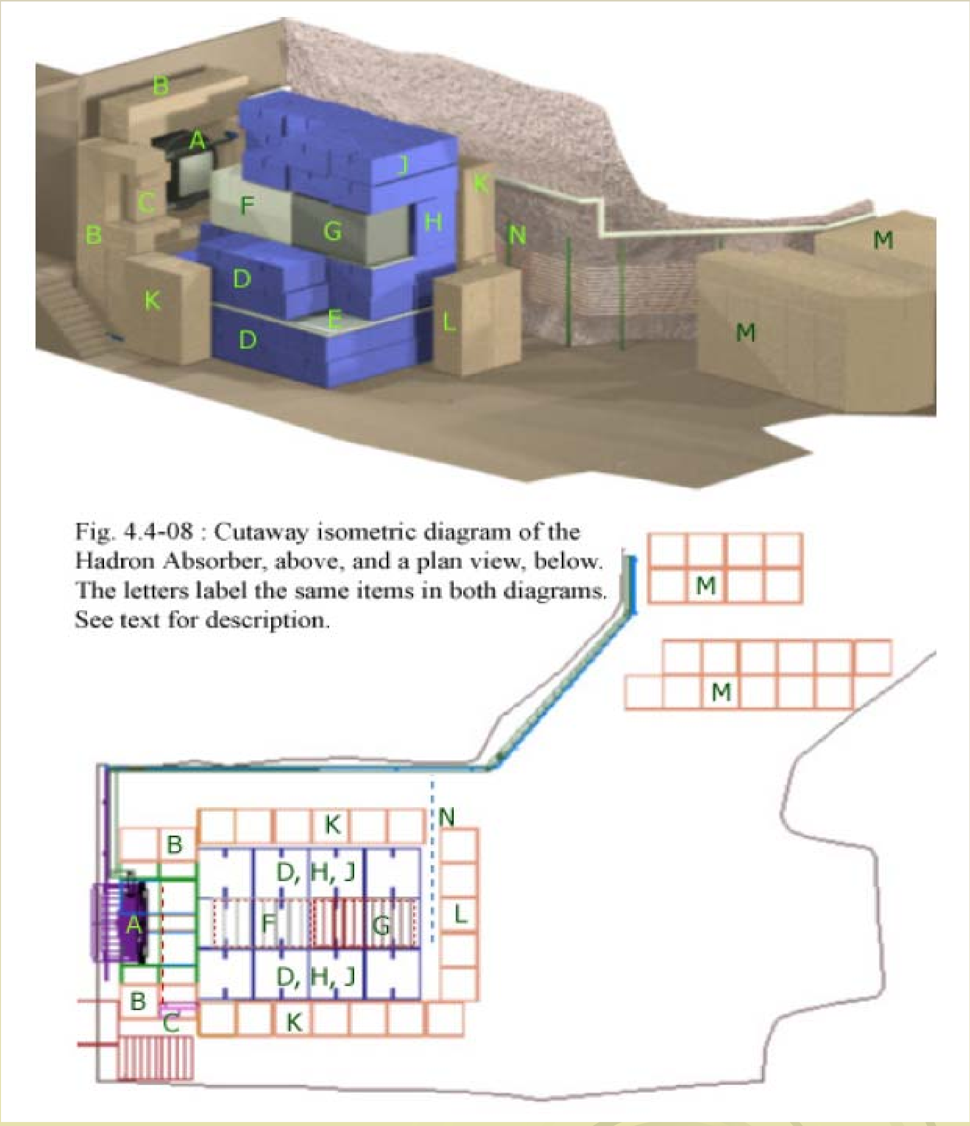


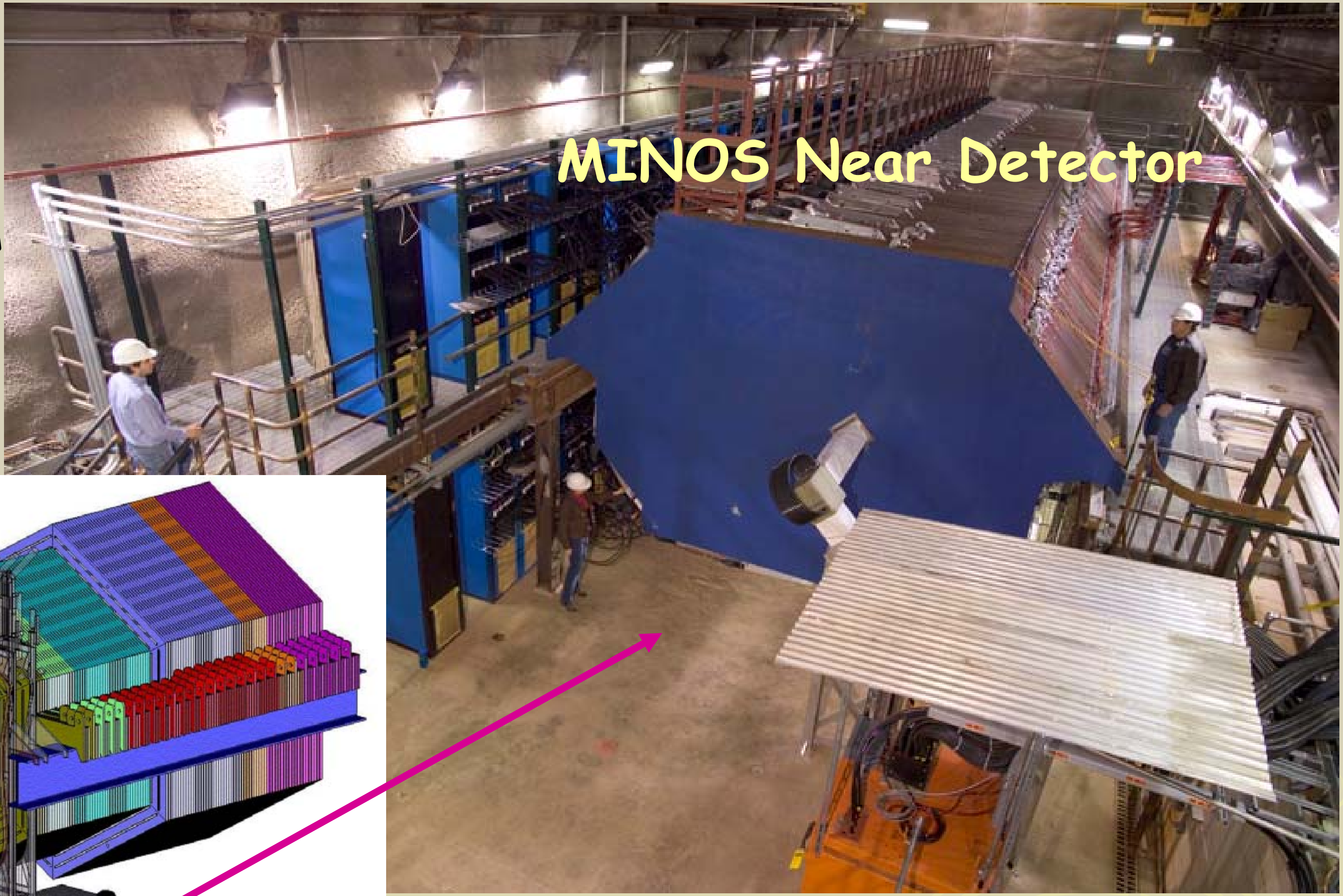
Fig. 4.4-08 : Cutaway isometric diagram of the Hadron Absorber, above, and a plan view, below. The letters label the same items in both diagrams. See text for description.

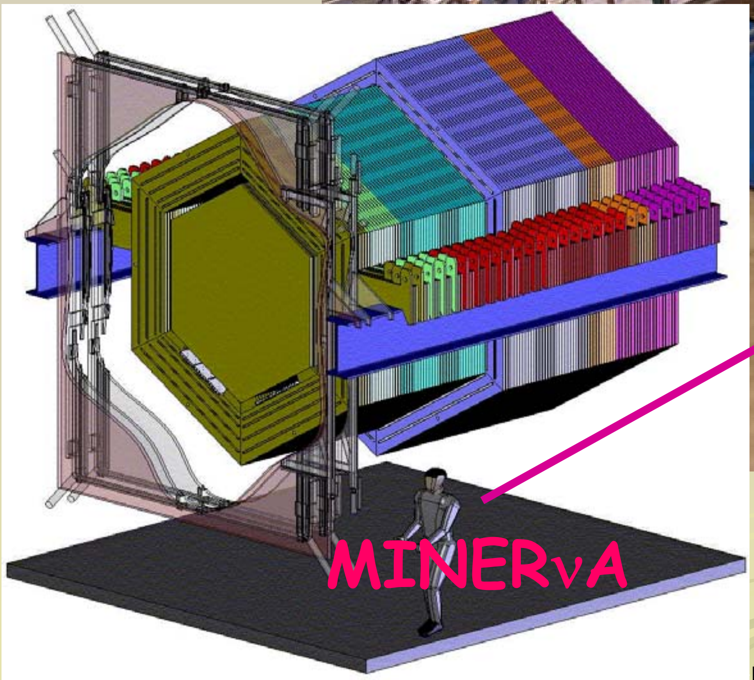
Water cooled Aluminum core, followed by Steel

Steel & concrete shielding

Near Hall and Detectors

Hall Size:
46×9x9 m





Beam Commissioning & Transition to Operations

Pre-Beam Commissioning

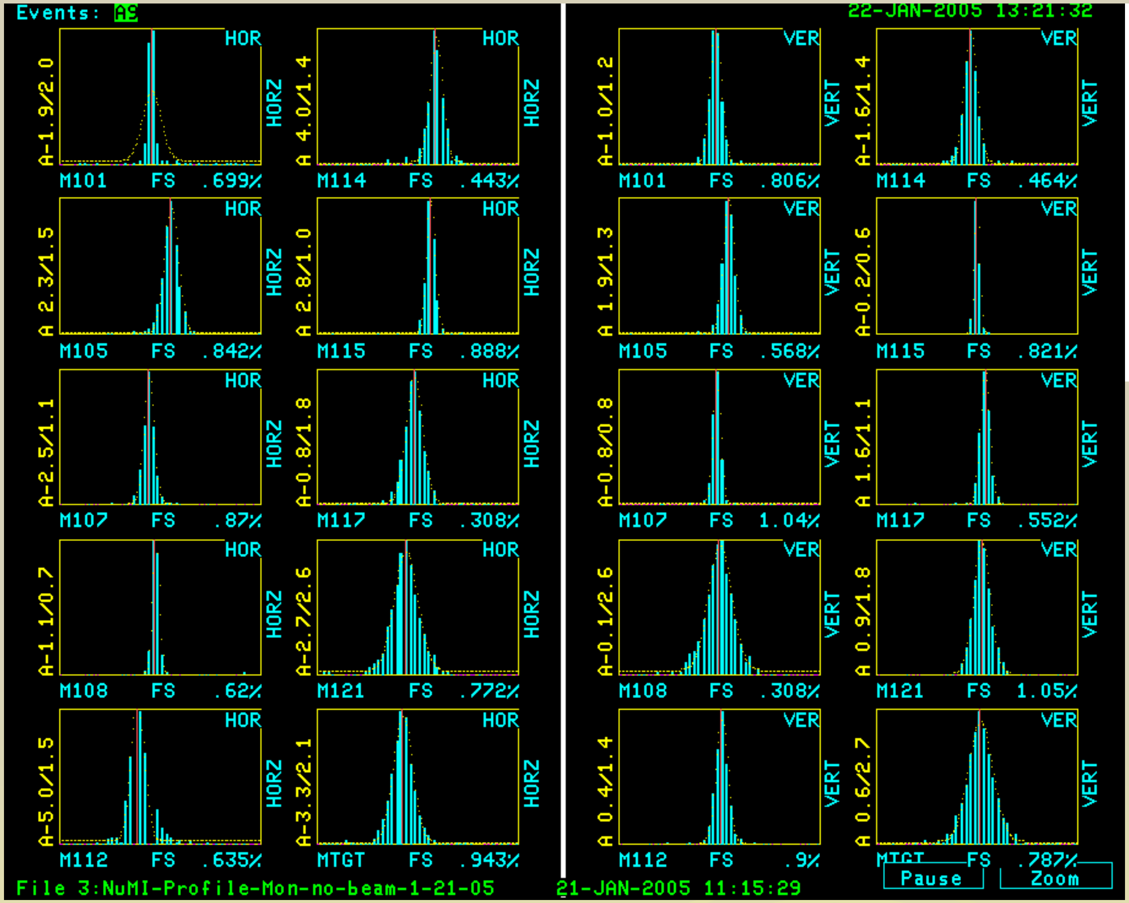
- **We planned to – and did – establish readiness of systems for primary beam prior to first extracted beam pulses.**
- These include:
  - Magnet function & connection polarities
  - Power supply function / ramp parameters
  - Kicker & power supply function
  - Recycler shielding from EPB fringe fields
  - Instrumentation function and readout polarities
  - Beam Permit System [establish & test 1st limits for all devices]
  - Control timing
  - Verify documentation capability – Beam profiles, positions, intensity, beam loss,etc.
  - Main Injector beam suitable for extraction

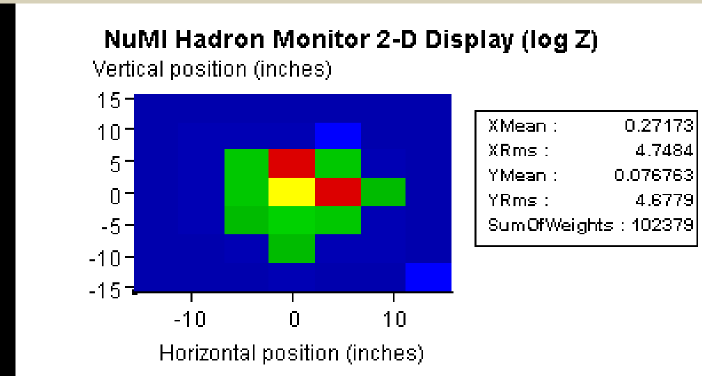
NuMI Initial Beam Commissioning

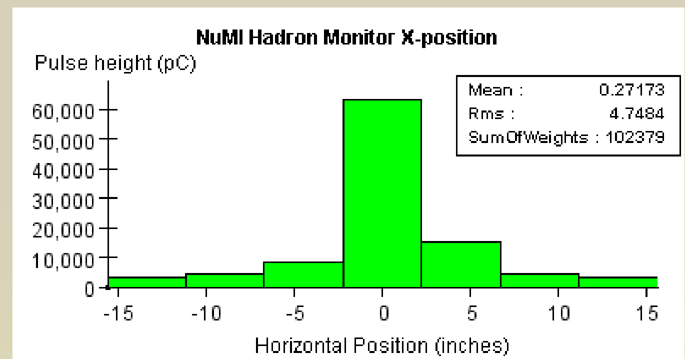
- **December 3-4 2004. Commissioning the primary proton beam**
  - target out, horns OFF
  - small number of low intensity (1 batch with 3×10^{11} protons) pulses carefully planned
  - beam extracted out of Main Injector on the 1st pulse
  - beam centered on the Hadron Absorber, 725 m away from the target, in 10 pulses
  - all instrumentation worked on the first pulse
- **January 21-23 2005. Commissioning of the neutrino beam**
  - target at z=-1 m from nominal $\Rightarrow$ pseudo-medium energy beam, horns ON
  - MI operating on a dedicated NuMI cycle, at 1 cycle/minute, with a single batch of 2.6×10^{12} protons, few pulses up to 4×10^{12} protons
  - final tuning of the proton line
  - neutrino interactions observed in Near Detector
  - NuMI project met DoE CD4 goal (project completion)
- **February 18-22 2005. High intensity beam in the NuMI line**
  - MI operating on a dedicated NuMI cycle in multi-batch mode
  - with 6 batches, we achieved a maximum intensity of 2.5×10^{13} p/cycle

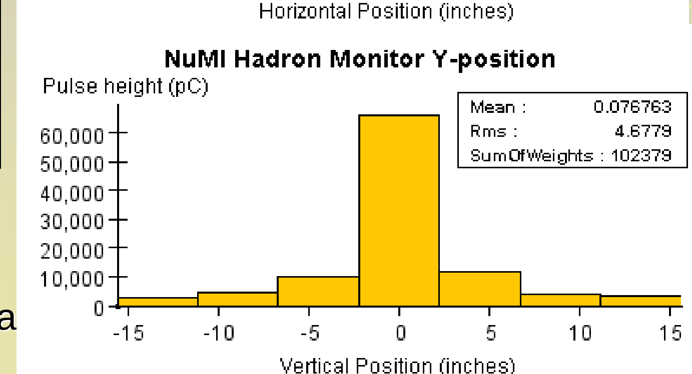
Beam Extraction in 10 Pulses achieved to hadron absorber at 1 km distance

December 3-4, 2004









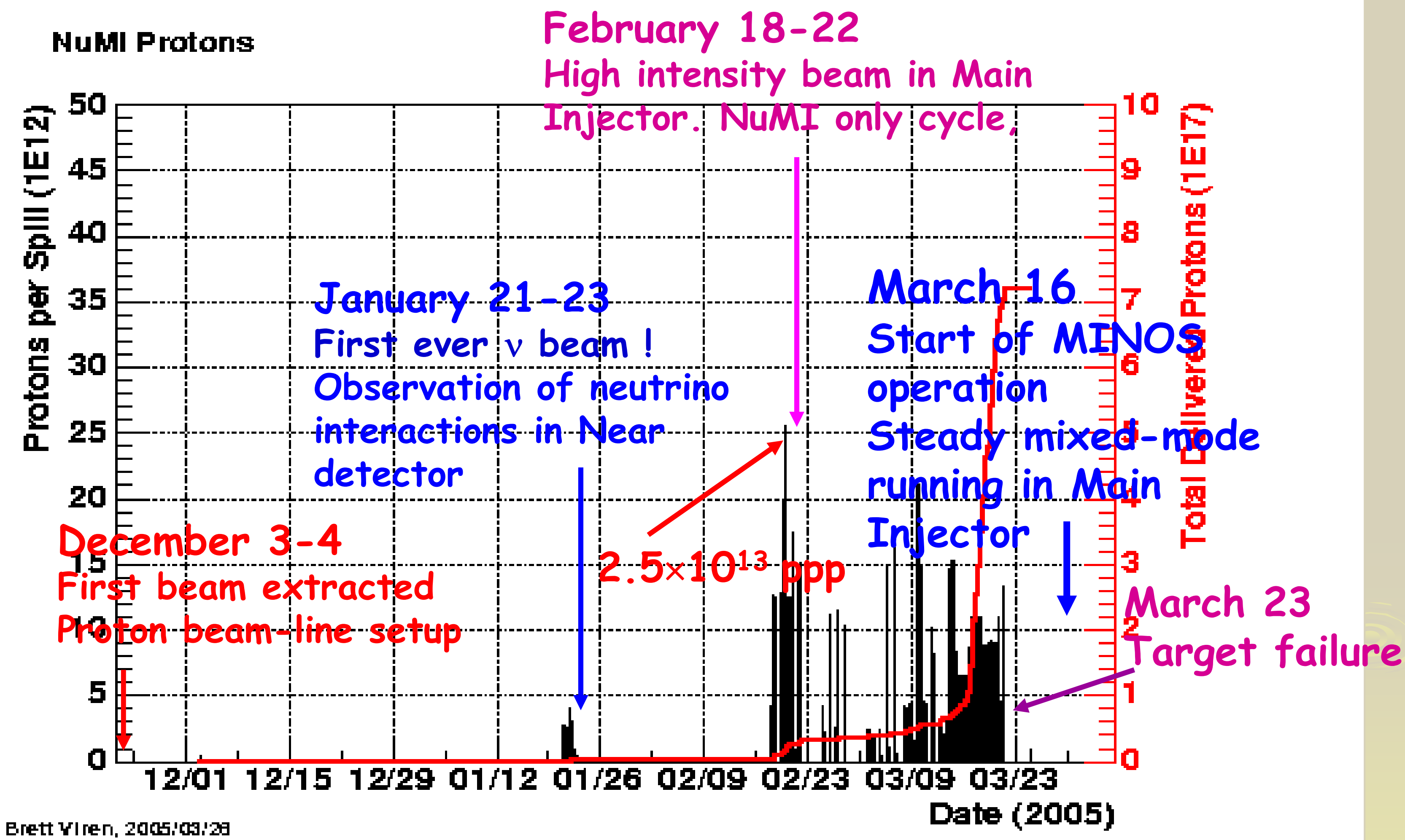
Profile monitor output along the beamline (few pulses later)
(from the extraction up to the target - ~ 400 m distance)

Most Significant Commissioning Challenge

- Interleaving beam commissioning schedule with delayed completion of target hall forced air chiller system.
- Priority to understand NuMI proton beam function while Main Injector and Collider still in start-up mode after lengthy shutdown.
  - Accomplish by discrete steps starting with very low intensity, and adding new capabilities as installation readiness completed.
    - 1st commissioning weekend was only 1.2E13 protons total with target out
    - 3rd commissioning period (10 weeks later) to 2.5E13 per pulse

  - Many thanks to Malika Meddahi for working with us during NuMI commissioning, and with our schedule uncertainties.

Beam Commissioning & Start up for Data Taking



Transition to Operations

- Transition to Operations –
  - **VERY** smooth
    - Restarted after target checkout in late April
    - Main Control Room Operators take control of running NuMI beam (12 May)
    - Initiate NuMI running during Recycler shot setup (18 May)
    - Initiate NuMI running during TeV shot setup (22 June)
      - **We needed to be a "low overhead" beam to Operators to have these running modes**

- Keys to NuMI Proton beam operation –
  - Comprehensive beam permit system : ~ 250 parameters monitored
  - Open extraction/primary beam apertures – capability of accepting range of extracted beam conditions
    - **Superb beam loss control**
  - Good beam transport stability
  - Autotune beam position control
    - **No manual control of NuMI beam during operation**

NuMI Beam Performance

NuMI 120 GeV Primary Beam

- Key specifications are:
  - Very low beam loss <1E-5 fractional loss for large regions of transport. (unshielded intense beam passing thru ground water reservoir)
  - Maintain position on target to 0.25 mm rms & angle to < 60 μrad.
  - Intense 400 kWatt beam => tight control over residual activation
- Overall performance:
  - A strong success.

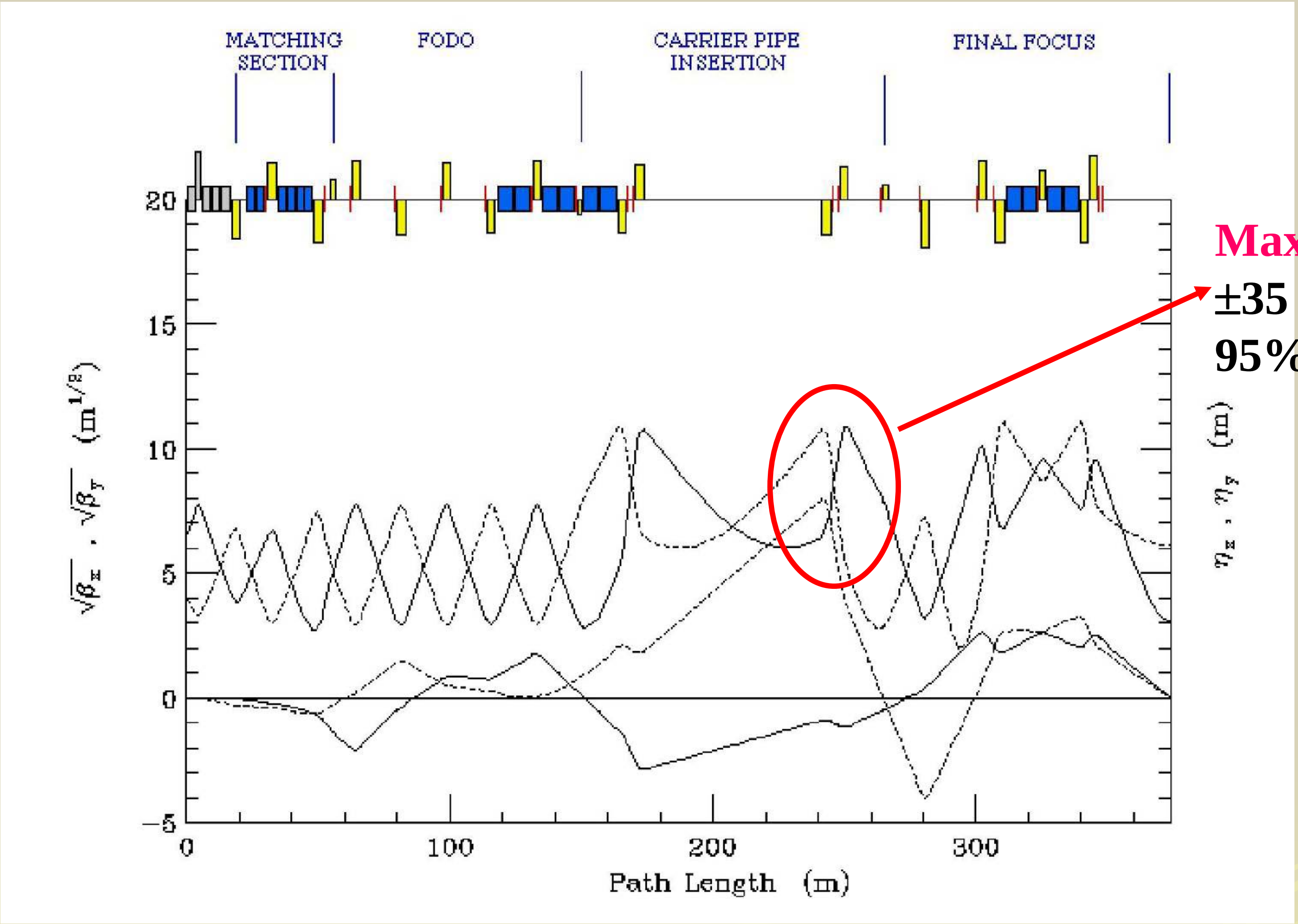
Kicker System Requirements

tightened specs during design process

	Early Requirement	Final Requirement
Integrated Field (120 GeV protons)	2.2 kG • m (550 μrad)	3.6 kG • m (900 μrad)
Number of Magnets	2	3
Field Flatness	± 1%	< ± 1 % (Best Effort)
Repeatability (over 8 hours)	± 1%	< ± 1/2% (Best Effort)
Field Rise Time	1.52 μs	
Flat top length	9.68 μs for 6 Batches, 8.08 μs for 5 Batches	
Magnetic Aperture	1.98 m x 10.7 cm x 5.2 cm (each magnet)	

C.Jensen lead enginer

Primary Beam Optics



Max. dispersion point

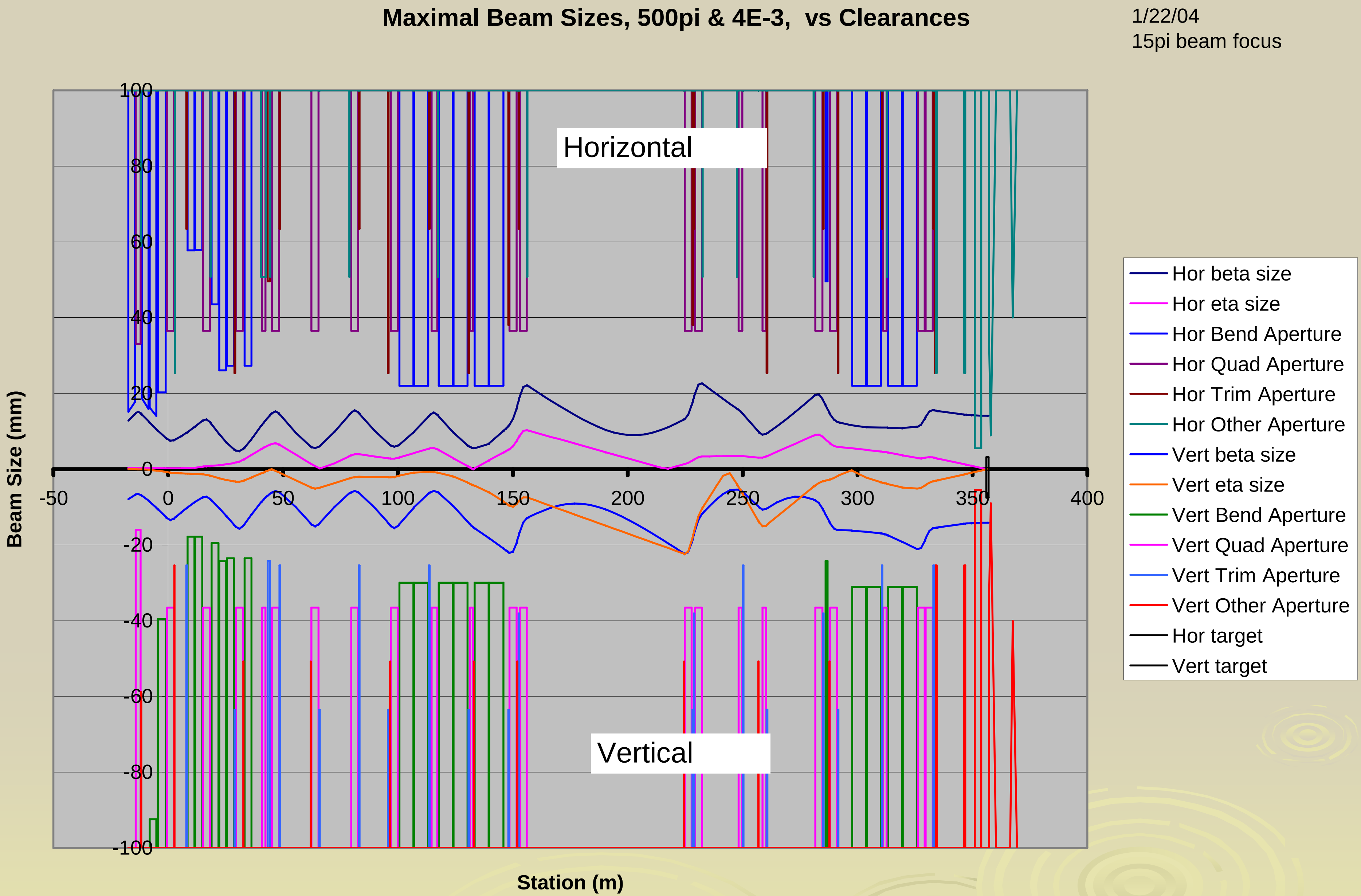
±35 mm aperture

95% beam size ±7 mm

Specifications: fractional beam losses below 10^{-5}

(Groundwater protection, residual activation)

1/22/04
15pi beam focus



NuMI Beam Permit System

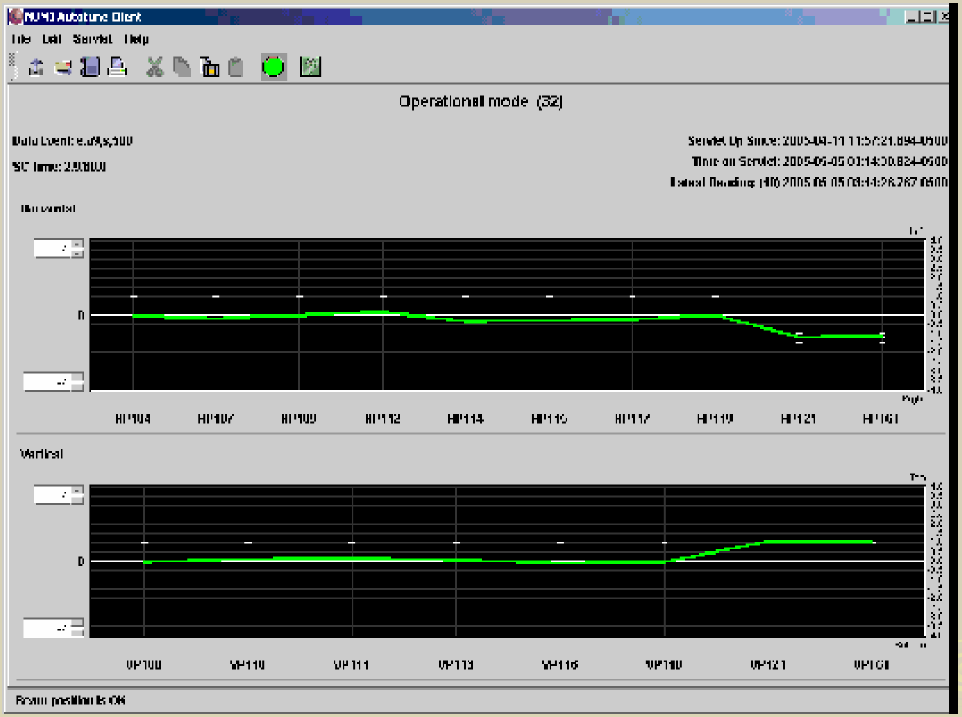
coordinated by R. Ducar

- Dedicated hardware based on Tevatron fast abort system
- Permit to fire NuMI extraction kicker is given prior to each beam pulse, based on good status from a comprehensive set of monitoring inputs
  - ~ 250 inputs to NuMI BPS
- Inputs include Main Injector beam quality prior to extraction, NuMI power supply status, target station and absorber status, beam loss and position for previous pulse
- NuMI BPS was prototyped with MiniBooNE, with excellent results
- Very similar in function to LHC,CNGS beam interlock system

With the very intense NuMI beam, perhaps our most important operational tool.

Autotune Primary Beam Position Control

- Automatic adjustment of correctors using BPM positions to maintain primary transport & targeting positions
- Commissioned at initial turn on for correctors
- Vernier control for targeting. Initiate tuning when positions 75 - 125 microns from nominal at target
- VERY robust for a given extraction mode. Refining for alternating (interleaved) extraction modes



Autotune Beam Control Monitor

Beam Performance plots

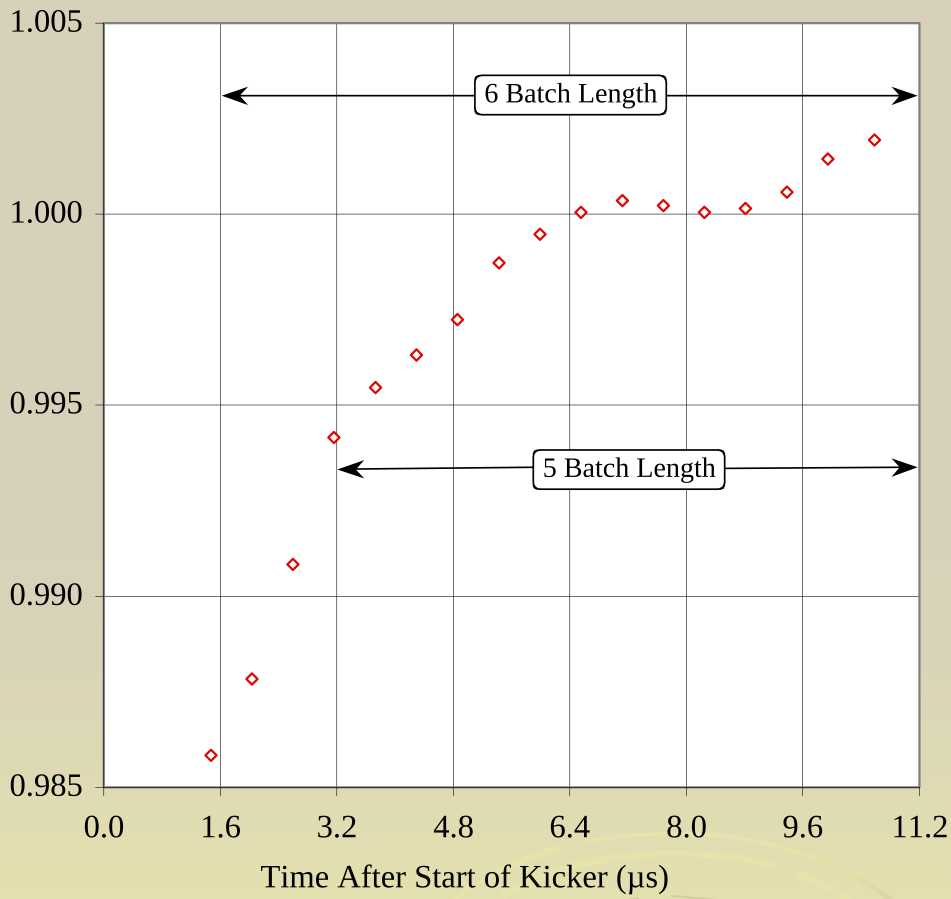
(most plots provided by M. Bishai, BNL)

- Kicker Stability

- Shown in plots for full month of Jan.'06
  - 2.0E19 POT this month
  - 0.98 E6 pulses
- Beam position stability
  - NuMI only, mixed and interleaved modes
- Pretarget beam widths
- Beam loss vs extraction mode

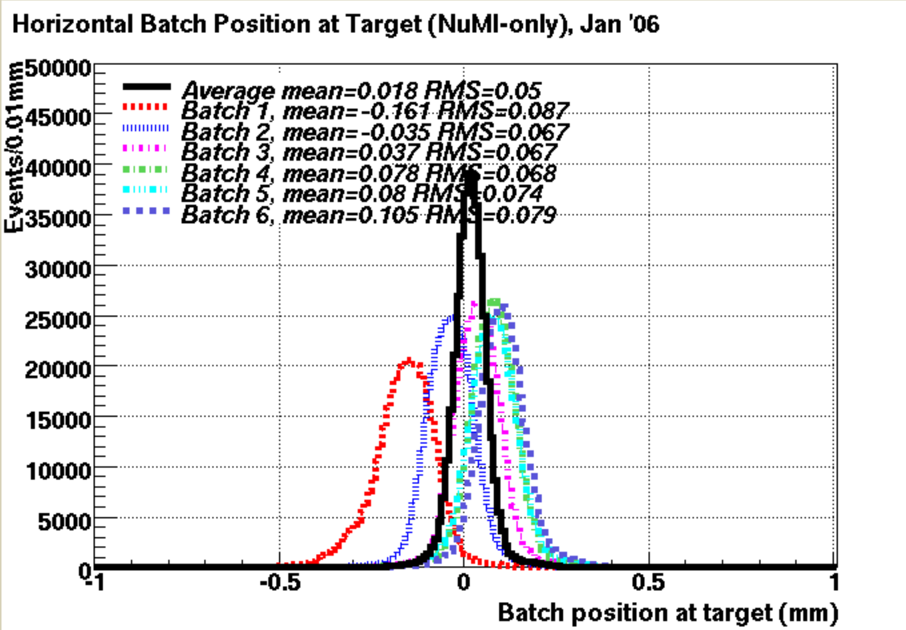
- Intensity, Beam Power & Downtimes for the 1st NuMI Year

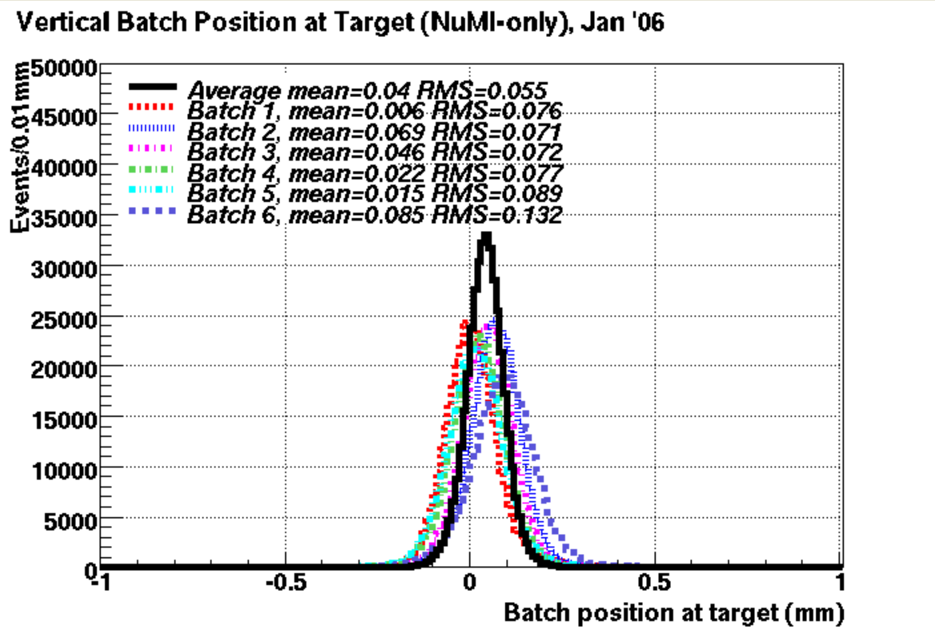
Measurement of Kicker Stability with Beam



- **Measured Change in Position**
- **BPM Accuracy of ~10 μm**
- **Total Displacement of 43 mm**

Jan. ‘06 Beam Stability on Target NuMI Only





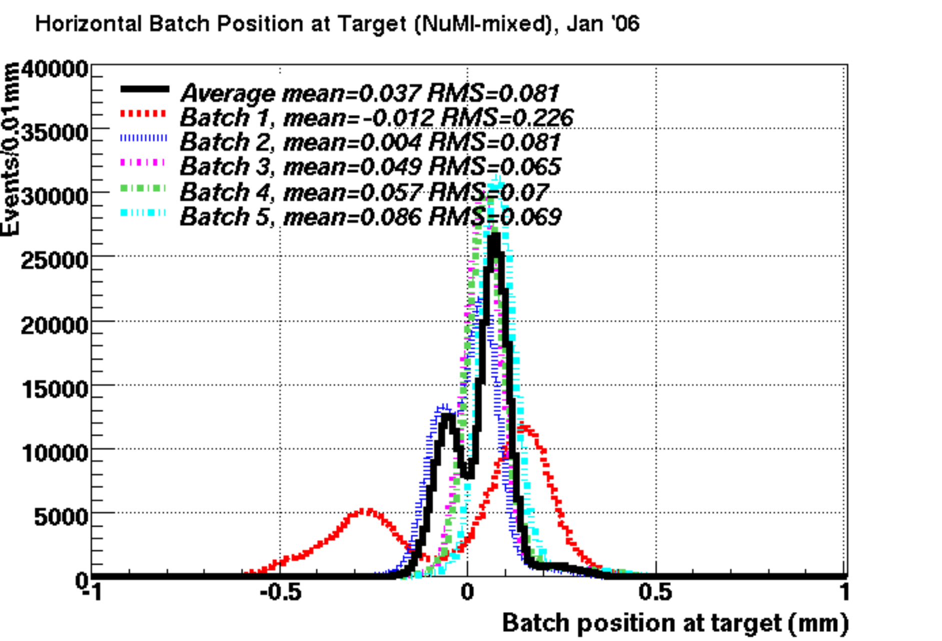
Hor

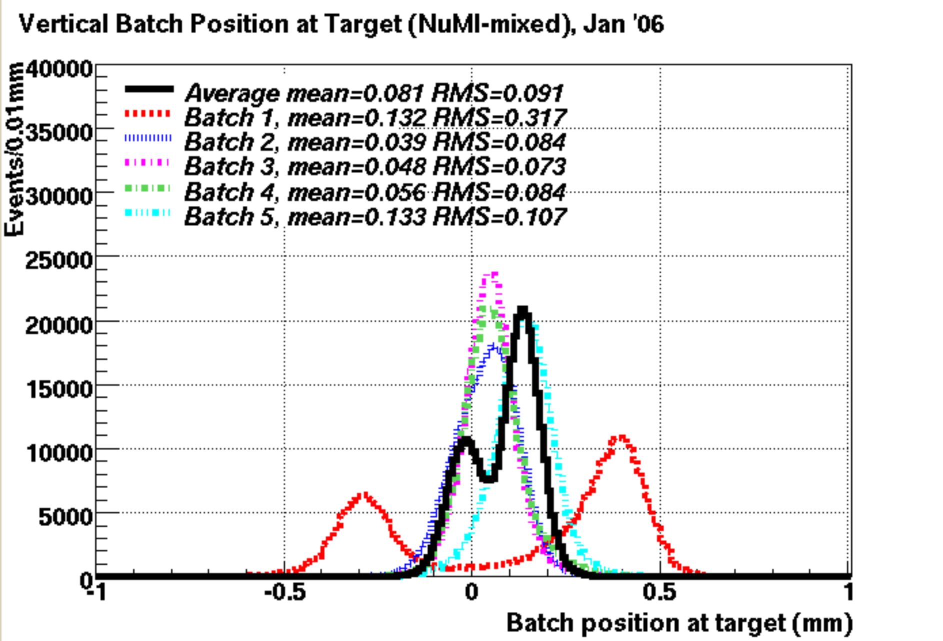
Ver

Note greatly expanded scale. Horizontal sees kicker stability effects.

Error on mean batch position < 60 microns for all batches (160 µ for batch 1)

Jan. ‘06 Beam Stability on Target Mixed Mode



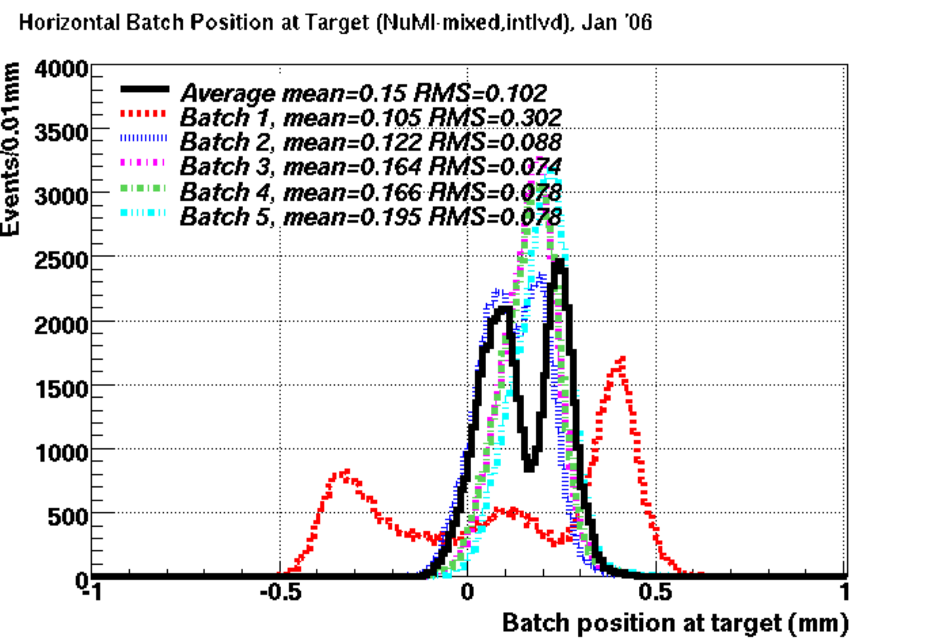


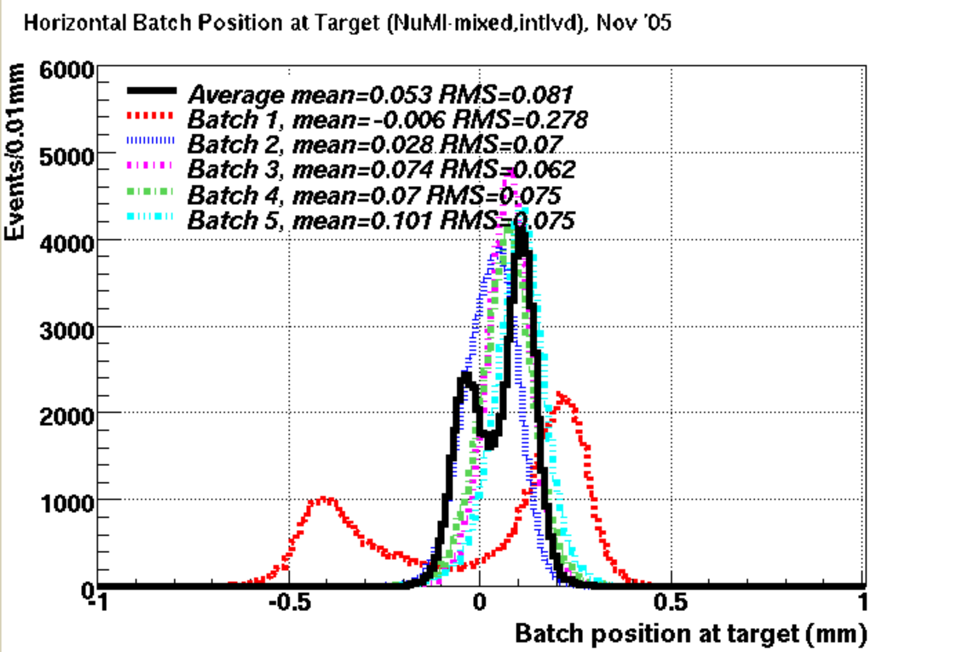
Hor

Ver

- Note bimodal effect of Pbar kicker on 1st NuMI batch [Either even or odd # turns between extractions]. Error on mean batch position increased to 90 µ. (Many batch 1 points > 250 µ spec.)

Beam Stability on Target Interleaved Mode



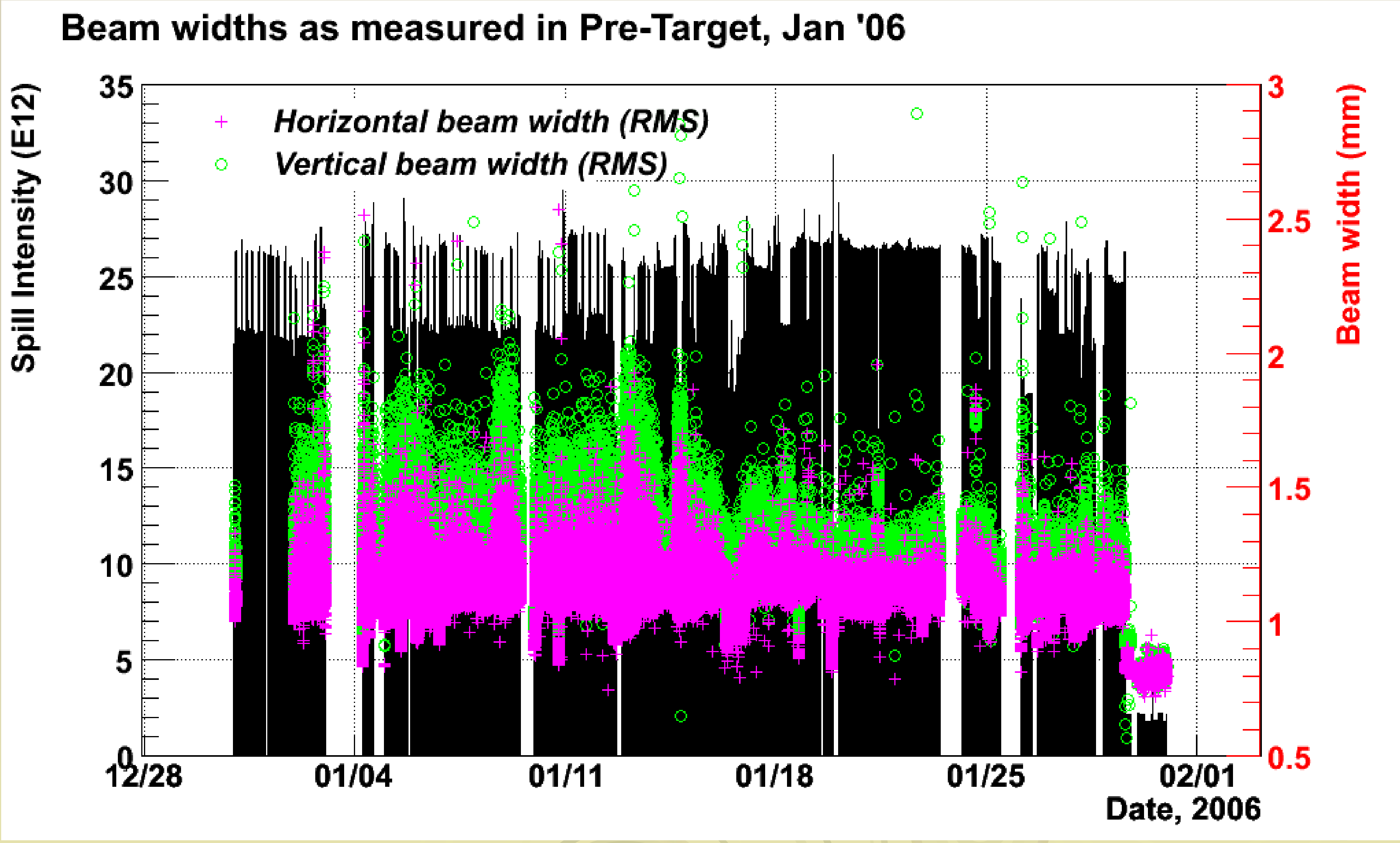


Jan 06

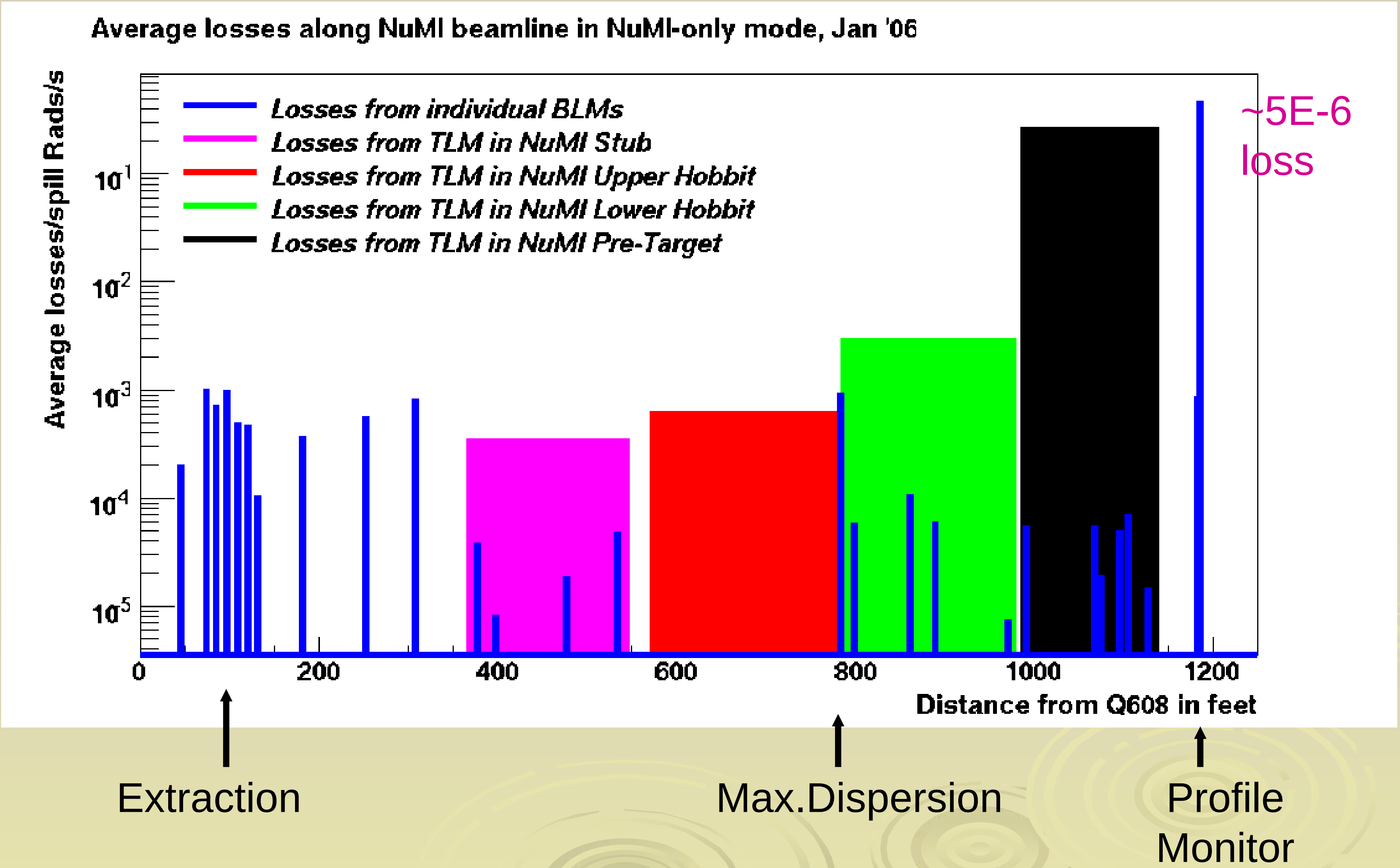
Nov.05

Some worsening of momentum difference between extraction modes. Are preparing separate Autotune corrector files for each.

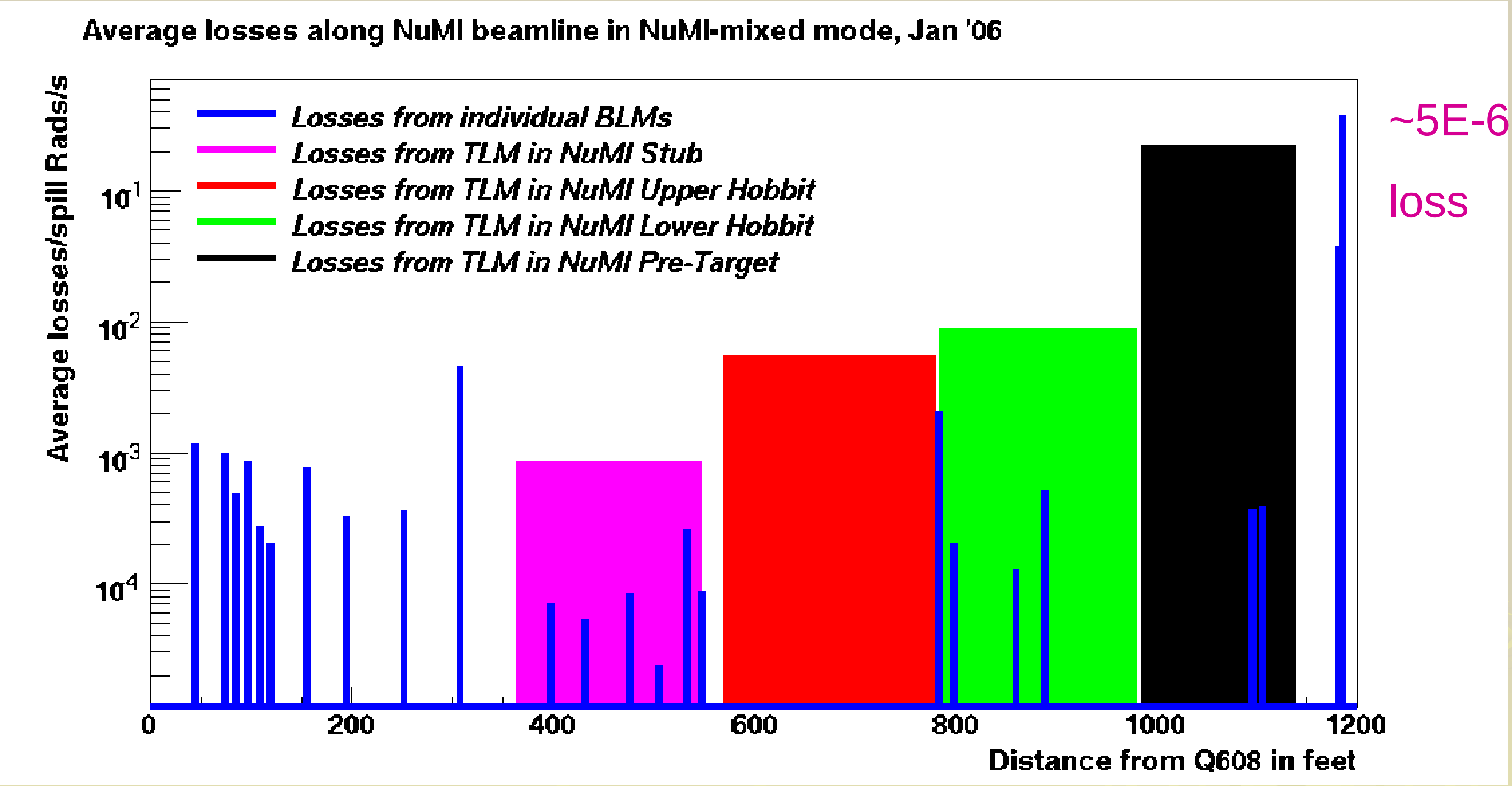
Jan ’06 Pretarget Beam Widths



Jan '06 Average per Pulse Primary Beam Loss – NuMI Only



Jan '06 Average per Pulse
Primary Beam Loss – Mixed Mode



~5E-6

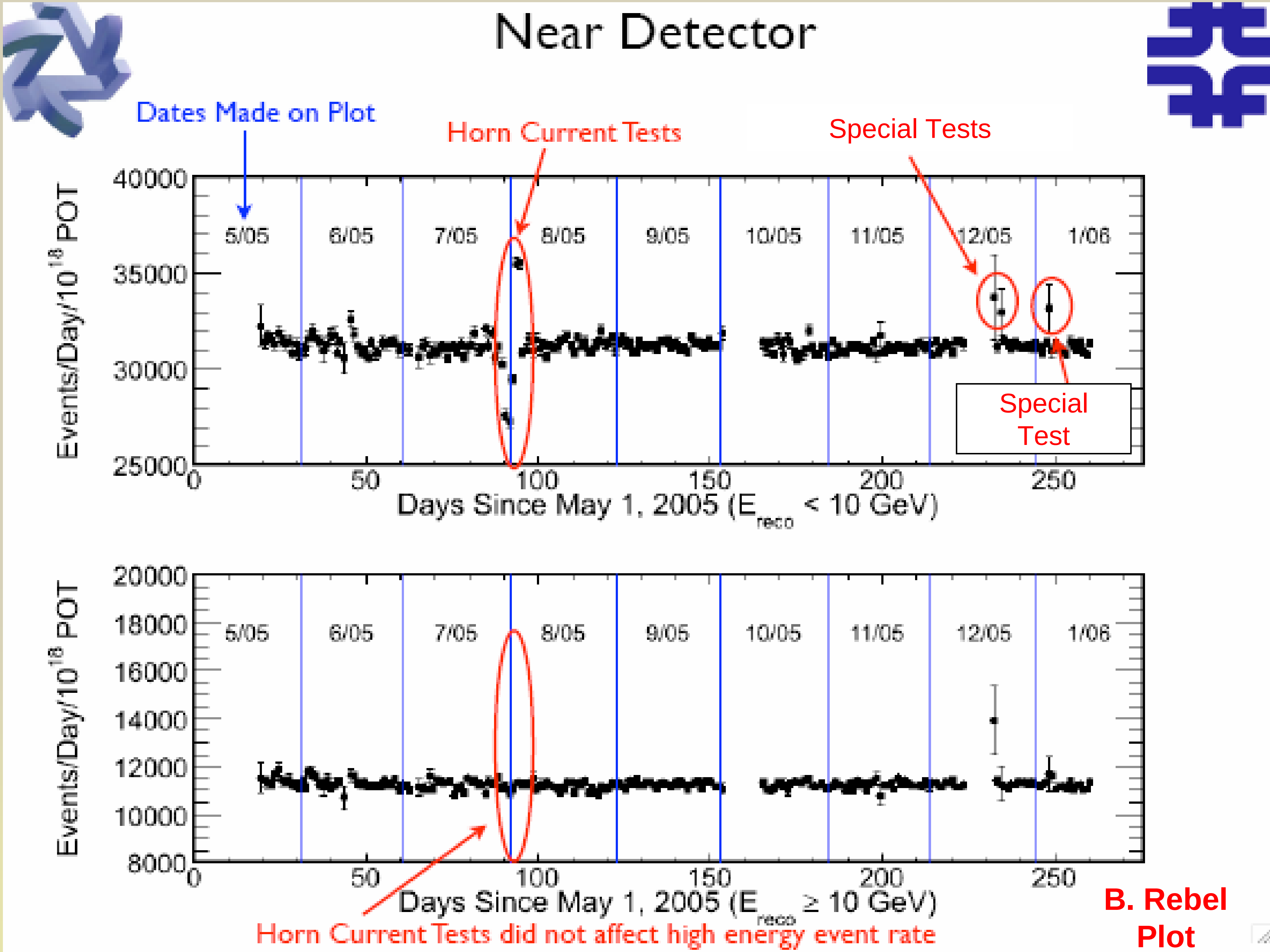
loss

Significant improvements in earlier loss from Pbar slip stacked batch

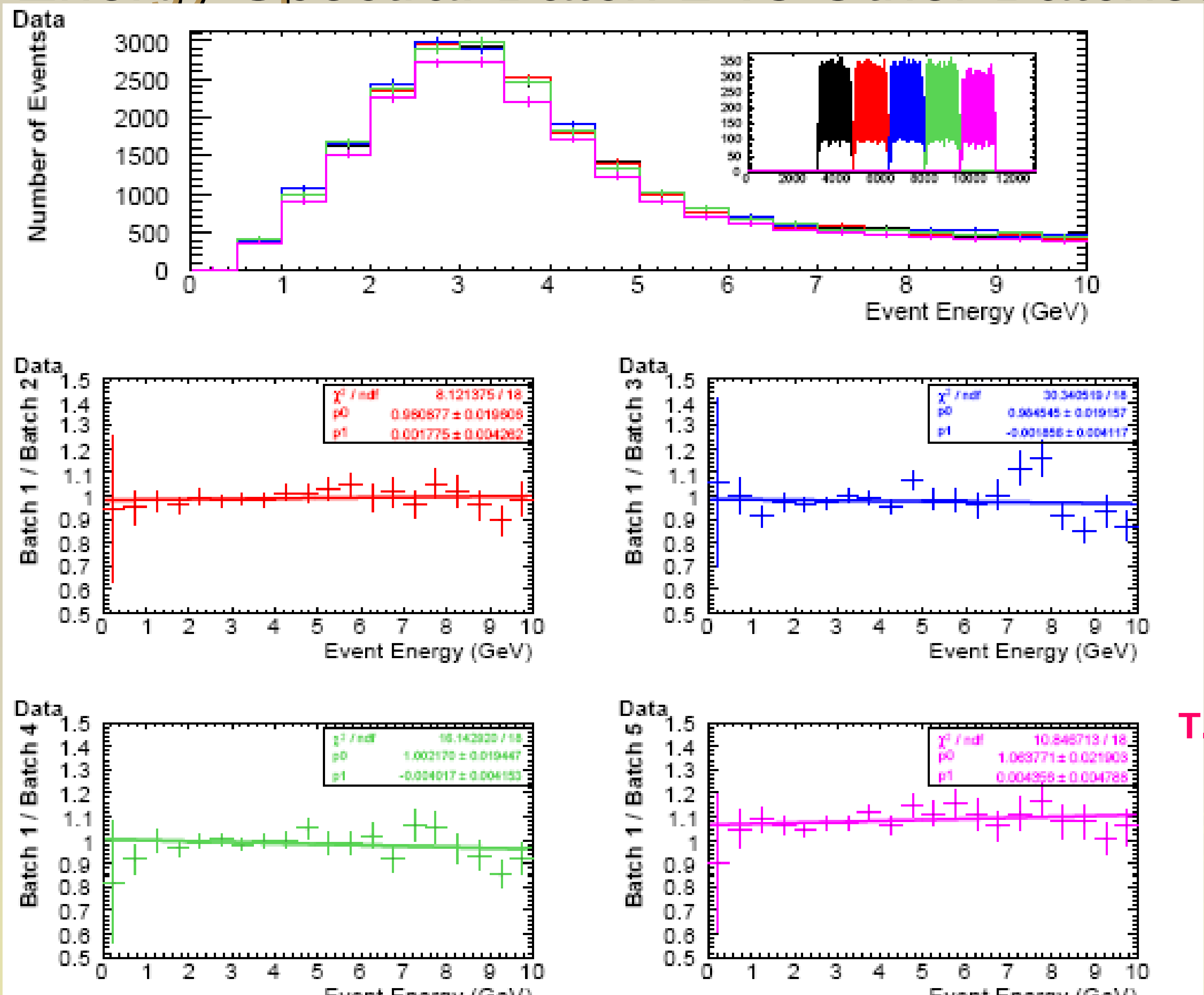
Progression to Increased Beam Power

- Keys to improving beam power for NuMI have included:
  - Continuing enhancement in accelerator intensity capability and control of beam loss – especially for pbar slip stacking process
    - NuMi only operation has been very smooth from the beginning, but this is not the normal operational mode
  - Steady improvement in number of beam cycles available for NuMI
    - Running during Recycler and Tevatron shot transfers
    - Adapting operational modes to interleave extra NuMI cycles as pbar stacking cycle times increase (due to stacktail core cooling limitations as stack increases)
  - Targeting highest possible intensity in NuMI only mode
    - Since 20 Sep.'05 when spare NuMI target was ready

Normalized Neutrino Rates vs Time



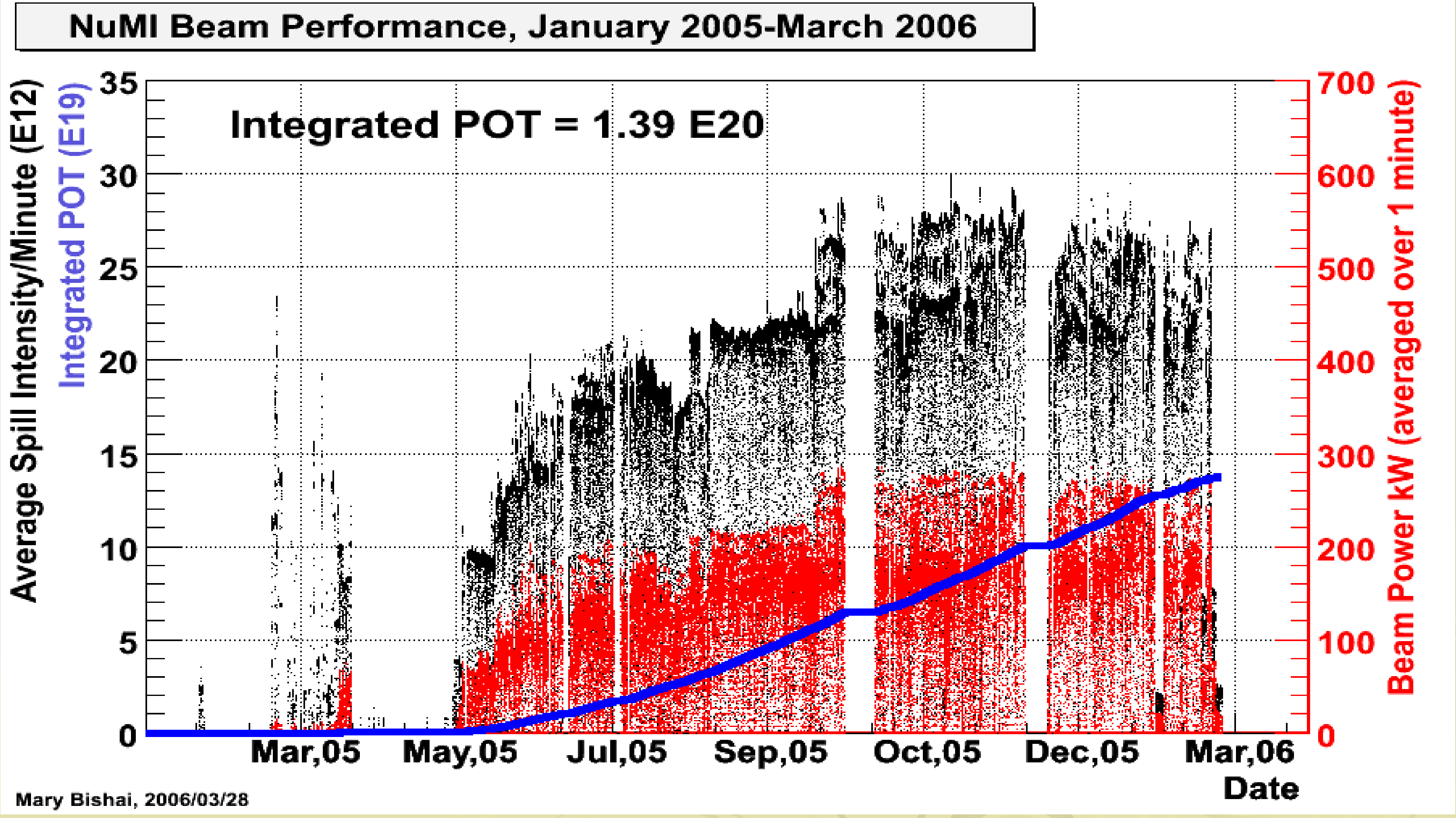
Near Detector
CC Energy Spectra: Batch 1 vs Other Batches



T. Osiecki Plot

NuMI Beam Year

Protons, Beam Power, Downtimes



Target Hall Systems

NuMI Target Hall Systems

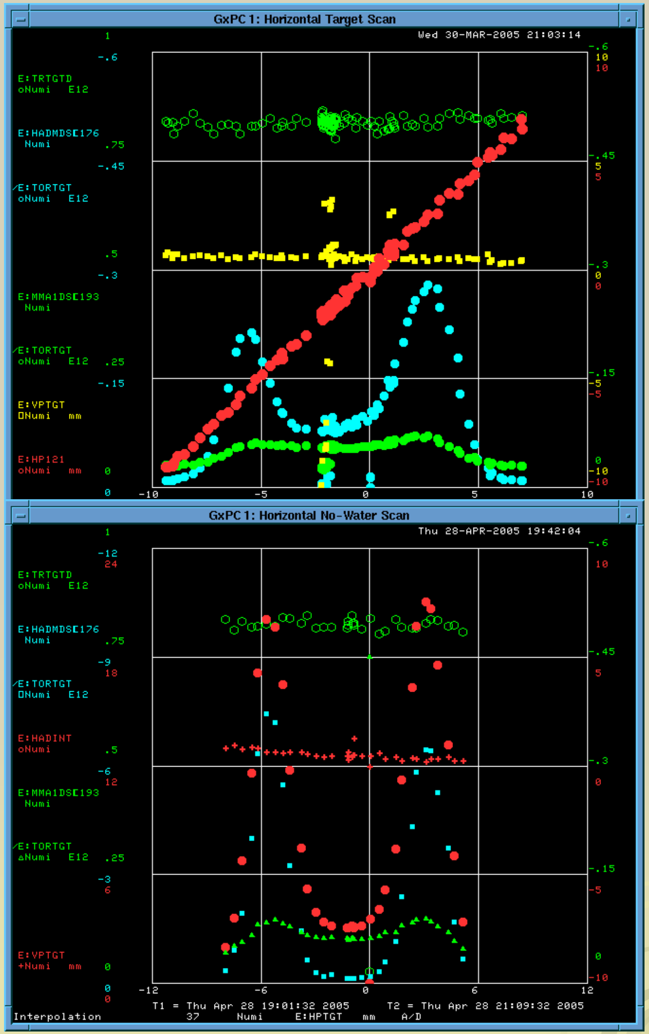
- Some VERY challenging one of a kind designs
- Graphite Target
  - Target integrity for intense fast spill beam
  - Low energy beam design precludes rigid support structure
- Horn & Reflector
  - Design for > 10 million pulses at 200 kAmps
  - Low mass to minimize secondary beam absorption
  - Intense radiation environment, moisture => corrosive effects
- Essential need for spares, with long lead times
  - Very difficult to repair relatively minor problems due to radiation
- 240 kW forced air target chase cooling system
  - Design constraints not as fundamental, but many challenges

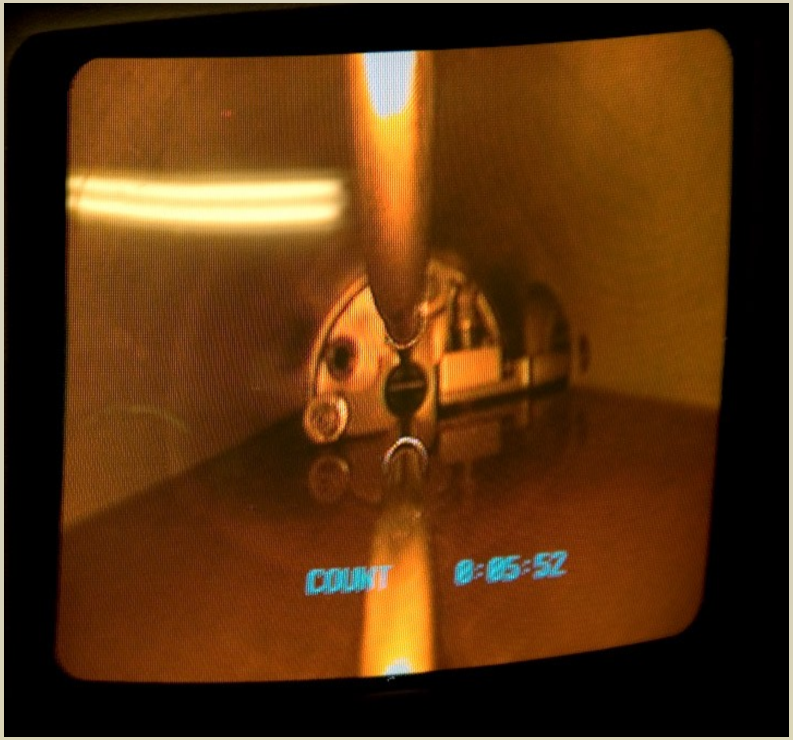
System Problems **and** Repairs

- Three significant component failures:
  - Target cooling line leak - Mar.'05
  - Horn 2 (reflector) hard ground fault – Oct. '05
  - Horn 2 cooling water flow return problem – Jan.-Feb.'06
- System designs have looked toward hot component replacement, not repair.
- Success here in addressing all three problems, and continue to use these components!!
  - Significant motivation from spare readiness
  - A VERY sustained effort by **J. Hylen** plus engineering teams

Target Scan using Hadron Monitor provides verification of major change – Mar. ‘05

Scan after water leak





Normal target scan

Target Diagnosis Period

- No NuMI beam for ~ 1 month while work to diagnose target cooling water leak
- Target removed from beam chase to hot cell
  - Water leak has closed after moving target
  - Many diagnostic steps – no firm answer for cause of water leak
  - Modifications made to fill target vacuum vessel with He gas (small overpressure)
  - Water removed by combination of He pressure and vacuum pumping
- Replace target in beam chase in preparation for operation using He backpressure to hold water out.
- Leak reopens after 1st hours of beam again, but He backpressure technique has worked very well – **for the duration of the run.**

Horn 2 Ground Fault - Oct.'05

loose support foot on horn

Owl shift Sat. Oct. 1, hard ground fault of 1 ohm.

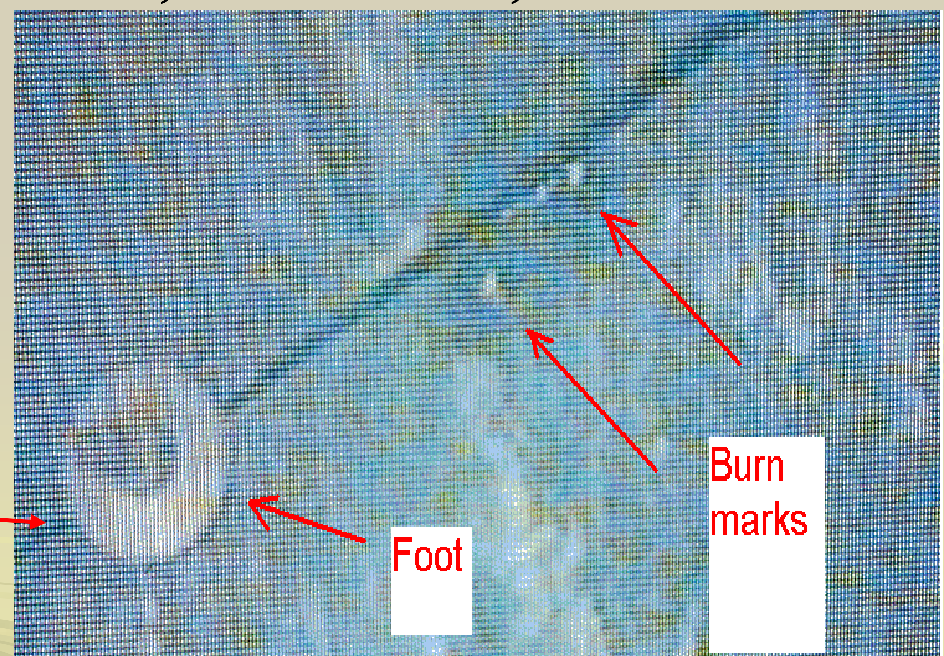
-when Horn 2 moved to work cell ground fault cleared

-foot left behind in chase, nut had vibrated off

-scorch marks seen under foot

Moved old foot, installed new foot

Wed Oct. 12, horn reinstalled,



Horn 2 before beam 4 cm clearance foot to floor

Horn 2 (Reflector) Repair
Apr. '06

Symptom: **Suction of water back from Horn 2 could not keep up with water spray rate to the horn –** ***water built up in the horn***

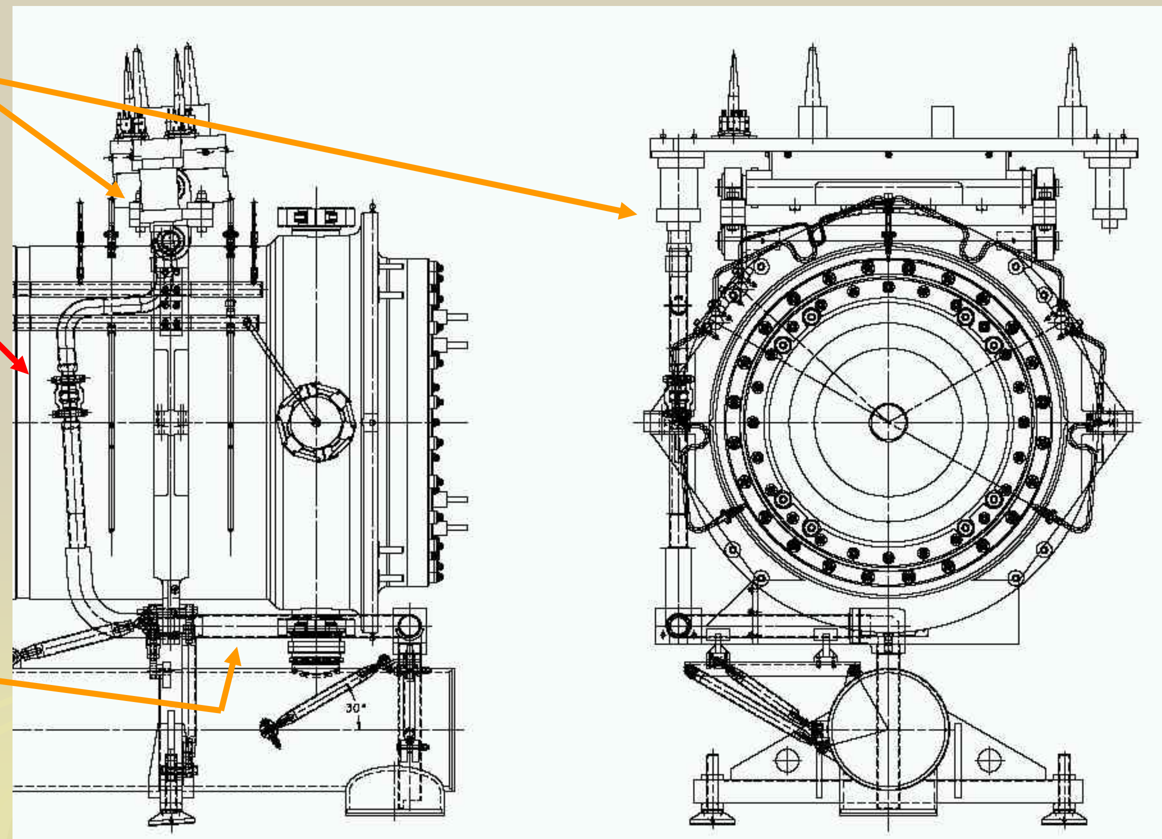
Swage-lock fitting
disconnect here

Problem: hole in suction line at ceramic electrical insulator drawing in air, reducing water suction

Repair: replace this section

Cut 5 cm stainless pipe here

Water collection tank

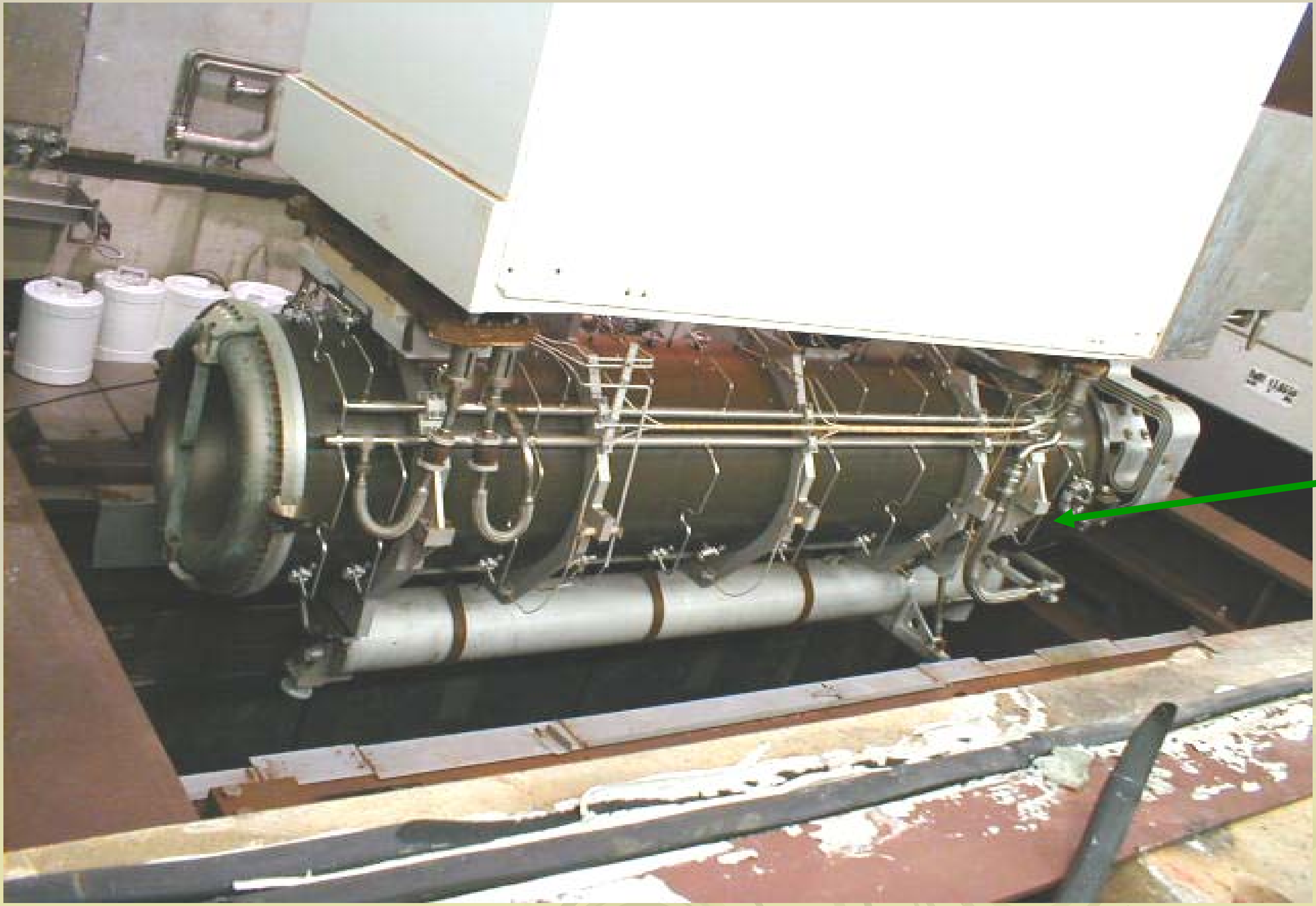


Challenge for Repair was the Residual Radiation Field

- 0.3 – 0.5 Sv/hr I chase around horn before component removal
- 0.08 Sv/hr on contact after horn removal
- Repair accomplished 18 Apr.
  - Checks good with no air or water leak
  - Hi-Pot acceptable
  - Preparing for horn pulsing vibration test

- The ALARA radiation plan estimated about 2.8 mSv to the repair crew including 25% for contingencies. (~ 10 µ Sv per second)
- The job was done with a total dose of 2.4 mSv. With an 8 person repair crew plus radiation safety supervision.
  - Extensive prior rehearsal for all steps.

Repaired Horn Returning to Target Chase



Repaired line

Summary

- A very eventful first year for NuMI beam operation.
- Strong successes in commissioning for all systems.
- Excellent Main injector and NuMI proton beam performance.
  - Significant ongoing efforts toward providing more POT
- A challenging and ultimately very successful first year with target hall systems
  - Our most important success was accomplishing system repairs
  - After 7.8 Million pulses, we continue with all original components
- Beam startup again after 3 month shutdown in June '06

Upcoming MINOS EP Seminar at CERN

- 5 Sept. 2006 – M. Kordosky
  - Report for the full MINOS data set currently collected
  - In conjunction with the NBI2006 Workshop

March 2006 result
with 0.93E 20 POT